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ORIGIN OF THE FILLED SINK-STRUCTURES AND CIRCLE DEPOSITS OF MISSOURI

By J Harlen Bretz

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Abstract

More than 1000 roofless solution cavities, filled with clay, shale, sandstone, coal, hematite, pyrites, galena, sphalerite, barite, and dolomitic debris, lie on the northern and western slopes of the Ozark dome. More than a score of geologists have proposed seven different concepts regarding the genesis of some of these cavities and their fillings. The favored three concepts are: (1) original surface sink holes; (2) collapsed caves; and, (3) gradual subsidence of overlying rocks keeping pace with solutional removal, under saturated conditions, of subjacent calcareous rock. The others are: (4) deposition of fills in unquiet seas; (5) dropping of fill material at intersection of faults; (6) collapse of superjacent filled caves into subjacent empty ones; and (7) localized upward thrust. This paper intends to show that the filled sinks and the circles constitute two different categories of solution cavities. The circles, properly defined, are collapsed caves but only concept (3) can explain the compressional deformations which the fills and cavity walls of the sinks exhibit.

Introduction

For nearly a century, geologists have been describing and interpreting unusual subsidence structures in southern and central Missouri, hundreds of which have been explored and mined for hematite, pyrites, coal, refractory clays, barite, and lead and zinc sulfides. All structures are due to removal of dolomite or limestone by ground water to make the cavities which are filled with subsided material, plus the contained mineral enrichments and replacements. The filled-sink structures, greatly preponderating over the circles, will receive most attention in this paper.

The most common name for this group is "filled sink structure." The term includes, in the concept, both deformed wall rock and the fill material which, also deformed, commonly belongs to much higher stratigraphic horizons.

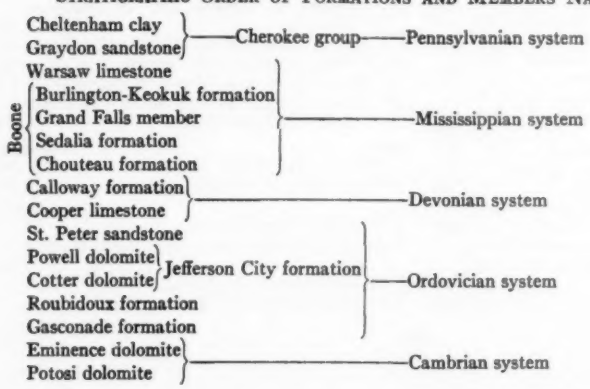
Three mechanisms for these subsidence structures have been repeatedly proposed: (1) filling of former topographic sinks, (2) collapse of roofs of former caves, and (3) gradual solution of subjacent calcareous rock with concomitant subsidence of already existing cover rock to become the fill.

This paper is concerned with presenting some new or previously unemphasized criteria bearing on the origin of these structures, their differentiation from circles, the elimination of some unsound arguments, the sharpening of some ideas about caves and sinks, and the revival of the third theory, which has been much neglected since Marbut's advocacy of it in 1907.

Acknowledgments

Parts of three field seasons have been spent on this investigation. Field study in 1946 was made possible by a grant from the Geological Society of America from the Penrose Bequest. Opportunity to extend the study, during 1947 and 1948, was generously granted by Director Edw. L. Clark while the writer was preparing a report on caves for the Missouri Geological Survey and Water Resources. Dr. Clark has also supplied much unpublished information on stratigraphy and the history of various mining operations. For interpretations in this paper, however, only the writer is to be held responsible.

Stratigraphic Order of Formations and Members Named in This Paper



Filled-Sink Structures

Definitions and Interpretations, from the Literature

These structures vary widely in their distribution; in their size, shape, or proportions; the structure of their wall rock and their fills; composition of fill; and time of formation. The only universal fact about the structures is that they are solution cavities in calcareous rock, occupied by a pre-peneplain downward intrusion of younger rock, both container and contained having been deformed during the intrusion. Even the distinction between container and contents is a doubtful one, for some members in the upper part of the wall rock may be traceable out into the fill, descending to become broken up but still a recognizable part of the debris.

Mather's (1946) definition was that "sink deposits" have "a funnel-shaped structure surrounded by a rim rock of limestone or sandstone. The rim rock dips toward the center of the deposit." His concept of genesis was that "large rooms," dissolved below the water table, suffered from wall and ceiling failure, with concomitant solutional removal of much of the fallen rock, until the roof collapsed and allowed overlying rocks to sag or fall into the cavity. His mechanism left no central cavity for precipitation of ores; they must occupy openings among "broken fragments . . . in all attitudes from vertical to horizontal." His wall rock was "undisturbed surrounding country rock," therefore his "funnel-shaped structure" must be the cavity filling within the confines of the rim rock.

Mather noted that "circle" deposits differ from sink deposits in almost every detail although both are "mineralized caved solution openings." Circles are bell-shaped or upright cone-shaped in cross section, and still filled with broken wall and ceiling rock. The sinks have lost most of such caved rock by subsequent solution, and their fill, of which rim rock is the outer part, was derived from higher stratigraphic levels. Circles do not have rim rock. Had the fallen debris in a circle been dissolved in sufficient amount, roof and upper wall support would have disappeared and the structure would, according to Mather, have been transformed into a sink.

Grawe's (1945) definition of a sink structure as "a basin-like arrangement of sedimentary strata which are sagged downward due to the differential solution of the rocks beneath" referred, entirely to the wall rock of his pyrites-containing structures, not to the fill. Grawe said a structure may be half a mile in diameter where the cavity fill is only a few hundred feet across.

The centripetally dipping beds of the surrounding calcareous rock were the consequence of vadose water migrating down the dip of initial sags toward a cavern, interstratal solution thinning the beds and thus producing the observed dips. Grawe inclined to the view that the pyrites fill is a cavern deposit, with or without associated replacement in the cave's wall rock. The deposit was made before or during the collapse of the enlarging cave's roof. Rim rocks and their downward extensions as in-dipping sandstone strata are part of the wall, even where vertical. Grawe's definition will not include those marked deformations which occur in the coal and refractory clay fills, nor those subsidence structures whose wall rock has no centripetal dips and therefore no peripheral rim rock outcrops. Grawe proposed to drop the term "filled sink" and substitute "sink structure."

Keller (1944) interpreted the clay-containing cavities as "old sink holes," commonly lined with sandstone which grades inward into sandy flint clay and that into relatively pure flint clay. The rim rock is the encircling outcrop of the sandstone. Nothing was said about wall rock as separate from the fill.

Branson (1944) said the "peculiar, pocket-like deposits of coal" seem to have been made "in sink holes."

McQueen (1943) looked almost entirely at the clay fillings which, unlike the pyrites deposits, have carried an original stratification down into the pit with them. In exploitation of the clay deposits, wall rock is rarely, if ever, exposed, and McQueen may never have seen in the clay-filled sinks what is so obvious in the iron-bearing sinks. He used the terms "sink-hole structure," "sink-hole type structure," "sink-hole type deposits," "sink type deposits" and "filled sink-hole type deposits." Rimrock, and its downward continuation as inclined sandstone strata, is part of the fill. It "lines the (clay) deposits."

The deformational structures in the clay (joints, faults, slickensides, folds, drag-folds) were ascribed to "collapse of caves and caverns," whereby the overlying Pennsylvanian clays, etc. "settled" and even "fell" into the open cavities beneath. McQueen opined that pyrites exist beneath the clay fills and that the iron-bearing sinks once had a clay fill above, now destroyed by erosional beveling of the Ozark upland.

The Kansas Geological Society's 15th Annual Guidebook (1941) contains a description and diagram by McQueen and Hinchey of a highway section in a sandstone-filled sink in Cooper County, labelled a "filled sink." The sandstone was described as St. Peter and the containing wall rock as Cotter dolomite. Both possess marked inward dip and minor folding.

Buehler (1939), writing of filled sinks containing fire clay, iron ores, sandstone, coal, and lead and zinc sulfides, gave his attention entirely to the character and structure of the intruded younger rock, with one reference to "the so-called rim rock which sometimes virturally encircles the sink area and consists of dipping beds of sandstone, the dip being toward the center of the sink area."

He believed that cavern-roof collapse accounted for all structures in subsided fill material, but seems to have believed that the iron ore fills were made in the cave before collapse occurred. He also believed that the sandstone masses surrounded by dolomite represented re-worked and re-deposited St. Peter, not subsided masses retaining their original integrity.

Tarr (1937) found the marcasite "sink-hole" deposits possessing an uneven contact with the country rock on all sides, commonly sharp but with the sulfide locally grading into the wall rock. He said nothing about structure in the wall rock and in only one of his eight diagrams is there a suggestion of in-dipping wall strata. The marcasite "structures" reported are all of mineral growths, not deformations. He supported the idea that the marcasite-containing sinks were originally caves and that the sulfide was deposited while the cavity was still roofed. His paper has elaborate diagrams showing "galleries" and "shafts" of these former caves. No excavated filled sink in Missouri has shown any such chambers.

Dake (1935), discussing the pre-Pennsylvanian surface in the Ozarks, was certain that many reported Pennsylvanian basal conglomerates are only "solution breccias", the consequence of cavern collapse. He classified centripetal dips into three categories: (1) the dips are limited to the older strata and the Pennsylvanian is horizontal; (2) the older beds are horizontal and the younger are considerably inclined; and (3) both the underlying and the overlying strata dip about equally. "Each instance affords a separate problem." Dake repeated such expressions as "cave fillings" and "cavern-collapse" but his paper also contains the idea that where both older wall rock and contained Pennsylvanian strata share in the deformation, "subsequent solution in the underlying dolomite or limestone" has produced "resulting settling of the strata."

Tarr (1918) found barite filling "the openings between large blocks of dolomite which lie at all angles to the bedding planes on the side of the (former) cave." Tabular crystals weighing several pounds occur embedded in a very plastic chocolate-brown clay, also occurring in these interstices.

Lee (1913) found both hematite-pyrites and refractory clay deposits in solution cavities within his area of study, also "cave conglomerates," "blossom rocks" and "filled fissures." He used the terms "filled sink structures," "filled caves," and "structural sinks." His text and map show that the structure, to his mind, includes the entire area of centripetally dipping older rock as well as the younger contents in the central part of the structure. "... the broken beds, where they have become exposed to the surface by subsequent erosion, show but slight disturbance about the rims of these structures and evidences of greater movements are increasingly apparent as the center is approached. The arrangement of beds in these structures corresponds in position to a flat, inverted cone of irregular form whose center is occupied by ... residual blocks and fragmental material." Sandstone rim rock, according to his diagrams, may make also an interrupted lining of the filled cavity. His conception of a pre-existing cave to give origin to the "filled sink structure" is obvious (1913, Fig. 10). His text and map legend specify

that the sandstone "blossom rocks" and the "cave conglomerates" likewise are cave fillings.

Crane's (1912) description of those structures containing hematite imply that a definition should include the in-dipping strata of the enclosing rock as well as the hematite filling. Replacement of both sandstone and dolomite in the wall rock has occurred. Seams of light-colored clay usually separate the hematite ore from the wall rock.

Crane thought that the filled-sink structure originated by "solution of the dolomite and subsequent caving of the overlying sandstone;" that caving did not extend to the surface but that the opening was arched over by undisturbed sandstone or limestone. The present position of the filled sinks at the surface is the result of subsequent erosion. Crane mentioned "cap rock" as "generally more or less stratified and co-extensive with . . . (the rock of) the side walls." It consists of "somewhat confused but alternating layers of sandstone, residual clay, ocher, and ferrugineous chert."

Hinds (1912) used the term "coal pockets" and thought they were formed in "sink holes or narrow valleys." His Plate 18 shows in-dipping coal layers in one pocket.

Smith and Siebenthal (1907) described the breccia fills and cavity shapes of the Joplin district's "run" and "circle" deposits of lead and zinc sulfide, stating that both types show ample evidence of subsidence of younger materials in making the fills and in causing the minor faulting in down-dragged wall rock or between wall and fill. Their apt term was "solution faulting." Diagrams better than text indicate down-bending of marginal strata toward the solution-made cavity and its breccia fill. For these structures, a pre-Cherokee karst topography was required, Cherokee sediments then filling the caves and sink-holes. Bodily collapse of cavern roofs figured largely in making the downward-diverging, slickensided walls of circles. Further solution of the Boone country rock, presumably under the Cherokee shale cover, caused various readjustments in the breccia, shale and sandstone fillings. This last item seems to cover the idea of solution without open cavity making.

Marbut (1907) described five types of cavity fills in his area: (1) sandstone (*See* Lee's, 1913, "blossom rocks" and Buehler's, 1939, classification); (2) Burlington limestone masses surrounded by Ordovician dolomite *in situ*; (3) coal with shale; (4) refractory clay; and (5) circle deposits yielding lead and zinc sulfides.

Most of the sandstone masses are remnants of the St. Peter formation "brought to their present position by the solution of the underlying limestones and the settling of the sandstone into the solution cavities." They are not sink hole accumulations of re-worked St. Peter, for their bedding departs from horizontality and they have associated subjacent whitish clay with limestone fragments and cherts, "residue from limestone dissolved away to make room for the sandstone block."

Resting on Jefferson City and older formations, Burlington blocks up to many thousands of cubic feet in volume have disturbed bedding which simulates synclinal folding. Underlying rocks may be similarly affected for a few feet from the contact. Between the Burlington and subjacent rock almost universally are clay and rock fragments resulting from the solution of limestone, chiefly the underlying rock. These Burlington masses "have been let down into the Ozark limestones by the local solution of the latter before the overlying Burlington was eroded away."

The shale and coal pockets are due to subterranean solution and consequent settling of portions of a once complete cover. "Underground erosion" has undermined them. A coal bed, dipping 30°–40°, owes its structure "wholly to disturbance since it was deposited."

Flint-clay and fire-clay deposits of Marbut's area usually show dip of stratification toward centers of deposits.

Marbut was fairly explicit in asking for solution without production of open cavities, the settlement of superjacent rock occurring *pari passu* with the removal of calcareous subjacent rock. Marbut's is the most definite statement in the literature of the concept of solution without open cavities, the fill descending continuously as the solution went on. Interstratal solution was urged, also, as the cause of wavy stratification in thin sandstone beds in the Jefferson City formation, the dolomite beneath developing an irregular solutional surface to which the sandstone has conformed under load.

Van Horn (1905) found both filled sinks containing coal and shale and circles yielding lead and zinc, in his area. Coal mining revealed that both coal and shale are extensively slickensided, faulted and folded and apparently also brecciated, boulder-sized shale fragments being embedded in deformed coal. Masses of tilted Burlington limestone were reported in one coal deposit.

The richest mineralization of the circles was along the contact zone between the core breccia and the wall rock, the ores ramifying into both.

Van Horn found isolated masses of Burlington limestone down in Jefferson City dolomite, dipping toward the center of the tract, more steeply in the lower beds. A conglomerate of chert, sandstone, and "cotton rock" dolomite in a limestone matrix locally separated the Burlington from the Jefferson City.

He also found exposures of the "Saline Creek cave-conglomerate" as much as 15 feet thick, the boulders up to 3 and 4 feet in diameter and composed of cotton rock and reddish cherty dolomite (both from the Jefferson City formation), with a grayish-white dolomitic matrix. The Jefferson City wall rock dips toward the conglomerate, most steeply where closest.

Van Horn believed that the coal deposits were made in pre-existing depressions which, however, "in many instances . . . appear to have been subsequently widened and deepened in such a manner as partly to undermine the coal and to cause it to fall or slide from its original horizontal position." The subsided masses of Burlington are "probably due to gradual settling of the beds into caverns." The cave-conglomerate "has the appearance of having resulted from the action of surface waters draining into a sink hole." The indipping of Jefferson City strata "points to a sink hole or cave origin."

Ball and Smith (1903) found limited basin-like deposits of coal and shale, of Burlington limestone, and of "Saline Creek cave-conglomerate." In the coal mines, many included boulders and pebbles of limestone and sandstone were scratched and polished like glaciated fragments, the surfaces shining "under a lamp like huge mirrors." They were wrapped around by concentric layers of shale ("Phacoidal" structure of British geologists, Peach et al., 1907) which was "intensely slickensided." "A trail of small angular fragments extends away from some of the sandstone boulders, apparently the result of drag." In one cap rock "the shale protruded everywhere into the overlying limestone." Local dips of 35° to 75° occur in the Coal Measures rock but all "rapidly die out."

The lower shale locally grades down into the cave-conglomerate. At the type locality, the conglomerate is 60 feet thick and some boulders are 20 feet in diameter. They are derivec from all older formations, including upper Burlington. The matrix is argillaceous limestone, calcareous shale or calcareous sandstone. No stratification is shown. About structure in the wall rock of the clay, coal or conglomerate deposits, the author said only that "the surrounding rocks are virtually horizontal", and that contacts are very irregular and the dolomite wall rock "considerably brecciated."

Bedding in the subsided Burlington rock dips "as a rule, rather steeply and where typically exposed forms synclinal basins."

Ball and Smith favored pre-existing sink holes for accumulation of coal and shale, even computing for one coal deposit 32 feet thick an original thickness of 480 feet of peat. This deposit of coal and shale is 275 feet in diameter and 130 feet thick.

In two cases, cap rock of the same formation as the wall rock exists. If this was actually *in situ*, and more than a projecting ledge, Ball and Smith's belief in pre-Pennsylvanian caves, as well as sink holes, as repositories is understandable. It, however, forced them into arguing for post-Coal Measures folding to account for the steeper dips.

Bain (1901) thought that some of the smaller circles of the Central mining district might be filled-sink holes but that others there, and probably all in the Southwest district, were the consequence of dropping of the fill material at an intersection of faults.

Wheeler (1896) thought that the "flint clay deposits occupy former sink holes in the limestone, the underground outlet of which became clogged or choked, thus converting them into small ponds of lakelets that have confined the drainage of the contiguous country (p. 202)." "The quickly falling sand particles

along the fringe of the basin . . . would give the transition from the sandstone border (rim rock) to the pure central masses of clay (p. 207)."

Winslow (1894) believed that some of the lead-containing deposits were made in large cave chambers, the gangue being fallen wall and ceiling rock plus residual clay from the surface. In explaining circle deposits of lead, Winslow said that "they are fillings of caves which had vertical openings leading to the surface." He compared the central conical mass of broken rock with debris cones in existing large cave chambers which have a feeding sinkhole above.

Yet he seemed to think that the breccia deposits of southwestern Missouri recorded a subsidence that kept pace with solutional removal of limestone. Surface depressions made by this settling received later deposits, shale and coal pockets being specified. "Later subterranean solution would result in further settling under such pockets, causing the beds to assume steep dips, or even brecciating them and transporting the fragments to greater depths."

Nason (1892) was interested in the specular hematite fills of the higher part of the Ozark Plateau. He apparently did not see what Grawe later stressed; thinned and in-dipping layers of dolomite wall rock. His terms are "ore body," "ore deposits" and "pocket." The "disturbed sandstones" (rim rocks) are "bent and broken and they usually dip toward the ore deposit." The hematite is massive and was originally deposited as iron sulfide in already existing cavities. It is not, like the sandstone, a subsidence from higher levels. Yet he considered the sandstones to be part of the fill. Associated chert and clay are residual from the dolomite "which formerly occupied the place which the ore body now fills."

Nason visualized initial solution of the dolomite as producing a settlement in the sandstone, after which "a comparatively narrow cave" developed under the sag, its roof later to fall in "leaving what was before an underground stream now exposed to the open air." The ores were deposited in both open and still-roofed solution cavities after subsidence was complete. The iron was derived from once-overlying rock.

Pumpelly's (1886) ingenious but improbable suggestion was that each hematite-bearing sink records the existence of two caves, one in limestones or dolomites now vanished, the other directly beneath it in deeper-lying calcareous formations. The upper cave was the original repository of the ore, but its bottom fell out, and its contents and the subjacent sandstone (Roubidoux) shared in the fall, when the roof of the lower cave collapsed.

In still earlier accounts of the fills of sinks and circles (Broadhead, 1874; Schmidt, 1873; Meek, 1855), familiar features of dipping rim rock, brecciation of subsided sandstone, and steep and variable dips in coal and shale are recognized. There is, however, almost no mention of wall rock structures, and only brief suggestions are made as to origin of the cavities. Broadhead suggested (1) The coal may have been "drifted" into pre-existing basins, and (2) "the variable thickness and the great inclination to the horizon (of coal and shale) would indicate their deposition in an unquiet sea." Meek utilized an upthrust to make the circles of the Central mining district. It would seem that, except for meteoritic impact, every remotely logical idea for the origin of the Missouri filled-sink structures has been suggested.

One may feel, after this summary, that the filled-sink structures themselves must involve more than one mode of origin. Subdivisions of the group are feasible, even required, but there is no doubt of consanguinity in the deformation of fills and walls by subsidence of higher-lying materials into a solution-made cavity. The problem here attacked is the mode of the deformation. This paper will try to show that the idea of pre-existing sinkholes to receive the coal, shale, and rim rock, the refractory clay, and the "blossom rocks"[1] is wholly in error and that collapse of caves can not have made the deformational structures in the wall rocks and the fills. Slow subsidence under load is the only satisfactory explanation for the deformations. Cavity-making and fill-making therefore were contemporaneous.

Much of the elaborate folding and internal deformation in subsided rock masses, shown in most of the filled-sink structures, hardly

[1] See section on "Blossom rocks" for description and interpretation.

appreciated by earlier observers, may be compared with the intimate deformation commonly ascribed to Precambrian sediments, although flow cleavage and high-grade quartzitification are lacking. The prevalence of such detailed structures in all these filled sinks is taken to record slow compressional deformation under adequate load. There is almost no evidence for tensional stresses.

One must not, however, think of the folds and corrugations as like miniature folded mountain structures. Continuity of orientation along any observed strike, continuity of a fold itself, is characteristically lacking. A watersoaked folded newspaper laid flat across a funnel or flaring bowl and then jammed down into it should give a fair picture of the vagaries of stratal attitudes in these filled sink structures of Missouri.

The repeated arguments in this paper that slow solution-subsidence in phreatic groundwater levels was the mechanism which made the Missouri filled sinks must not be taken as denial that caves and topographic sinks have ever been a part of their early history.

Filled caves, with walls and roofs intact, are known in Missouri; none, however from those districts with filled sink structures. The writer's contention is that, in the sink structures under examination, the solutional subsidence has destroyed all record of any former caves or surface sinks, has made the detailed structures here emphasized as compressional deformations, and has lowered the fills below the bottom of any original caves or surface sinks.

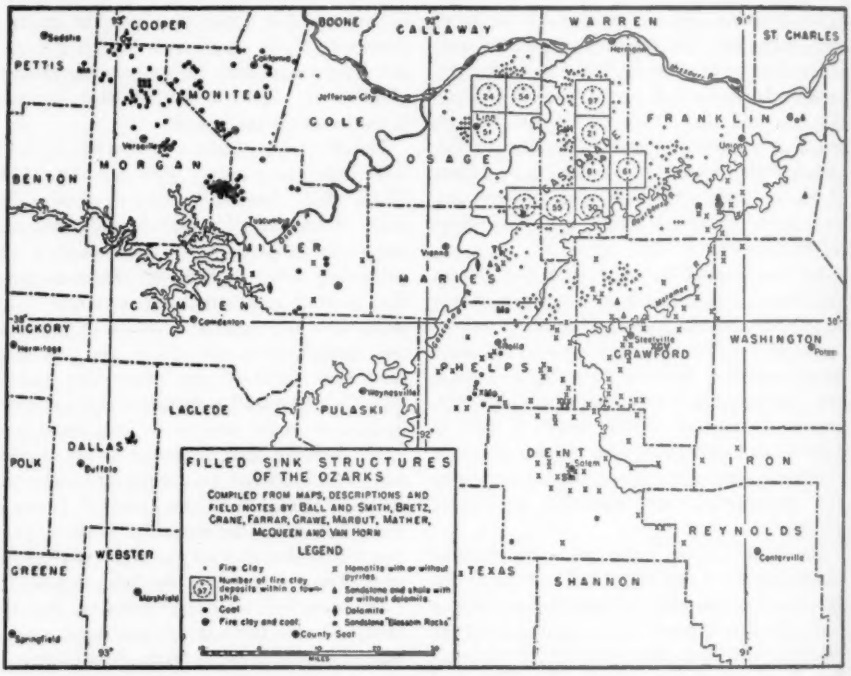


FIGURE 1.—FILLED SINK STRUCTURES OF THE OZARKS

Anaconda Coal and Clay Mine

This excellent showing of filled sink structure, frequently cited as typical, lies but a stone's throw south of the present location of U. S. Highway 66 between St. Clair and Stanton in Franklin County (NE ¼ NE ¼ sec. 8, T. 41 N., R. 1 W, Fig. 1 A). An abandoned gloryhole about 100 feet across and 40 feet deep is walled on the south by much

jointed but otherwise massive sandstone (rim rock) and elsewhere by steeply dipping fire clay. Open-pit mining of the central coal mass was finally abandoned and a shaft 140 feet deep was sunk alongside the pit. Coal was mined from this shaft to make a circular room about 100 feet in diameter. Drilling is reported to have shown at least 40 feet of coal below this room. On the side of the pit opposite the shaft, a drill hole penetrated 200 feet of fire clay and found no bottom. The entire fill of Pennsylvanian sandstone, clay, and coal is down in the Ordovician Jefferson City dolomite. No wall rock, however, is exposed.

In the pit, the sandstone rim rock had an essentially vertical contact with the clay, apparently a stratification plane, possibly a fault. The steep clay banks show a coaly layer in places around the periphery of the pit. This coal stands vertically or dips steeply toward the center of the structure. Strikes of the coal are tangents of the nearly circular pit. It is obviously a stratum in the upper part of the clay, occurring stratigraphically below the commercial coal body.

On the east side of the pit, this coaly layer shows sharp contact with clay beneath, i.e., nearer the outside of the deposit. The contact is corrugated to correspond with corrugations in the intimately and irregularly slickensided coaly layer and a few years ago showed an excellent drag fold about a foot in amplitude, now buried in slope waste.

The most complete description of the coal is by McQueen (1943, p. 172):

> A lens-shaped body "some 12 feet or more in thickness which had dropped or moved from a horizontal to a nearly vertical position during the formation of the containing sink-hole structure. Because the coal lens extended downward from the surface to a depth of 190 feet, it was erroneously credited with a thickness of that amount. An end of the lens was observed by the writer in the bottom of the underground workings. The overlap of the coal by the upper clay was quite obvious in the deeper workings."

Four significant structures bear on the origin of this filled-sink deposit: (1) The central coal deposit was nowhere more than 100 feet across and extended from the surface down at least 190 feet; (2) A nearly vertical clay body was wrapped around it in cylindrical fashion, the stratification conforming to this outline; (3) A nearly vertical sandstone rim rock, basal to the clay, descends 40 feet to the bottom on one side of the pit; and (4) Abundant irregular slickensides occur in the clay and the coaly layer, and between them is a corrugated, dragfolded contact.

These features clearly rule out the hypothesis that the sand, clay, and coal lie as they were deposited in a pre-existing topographic sink hole. Subsequent subsidence has carried the deposit down far below its original level in the country rock, thus producing the observed deformations and destroying the structures expectable in a sink hole fill.

Against the hypothesis of collapse into a subjacent cavern (Dake, 1935; Buehler, 1939) stand the following facts: (1) The ground plan outline, at least of the coal, is circular, whereas caves are linear. (2) The three sedimentary units have maintained their identity and relative positions during the entire subsidence; there has been no fragmentation to make a breccia of mingled sandstone, clay, and coal. (3) Slickensides and dragfolding in the coaly layer and the clay record detailed compressional deformation.

Regarding item 1, it might be argued that only a circular area of a linear cave's roof suffered collapse. But neither here nor in any other filled sink in Missouri is any known, positive evidence of survival of cave chambers leading away from the approximately equidimensional sink structures.

Item 2 can be adjusted to the cavern collapse hypothesis only by having the sandstone all fall first, the clay afterward, and the coal last, or by having one collapse of all three members together. But the cylindrical pattern of vertical clay encircling vertical coal would remain unexplained. If separate falls occurred, each unit should at least be a self-brecciated mass. This clearly is not true of the clay and coal, and is not indicated for the sandstone.

Item 3 seems an indisputable record of slow downward penetration, the weak clay and coal members maintaining their unity and relative positions because held tightly together at all times. They yielded, under an adequate superincumbent load, as space below was provided by gradual solutional removal of the underlying Jefferson City dolomite.

This solution appears to have occurred chiefly at the bottom of the intruding mass. If widening of any considerable amount had accompanied the deepening, the vertical position of the bedding could hardly have resulted. the north wall at angles about twice as steep as any dips shown in the face of the section. The "rim rocks" (Fig. 2) diverge northward with a horizontal angle of about 50° between the two sets. Thus the central and deepest

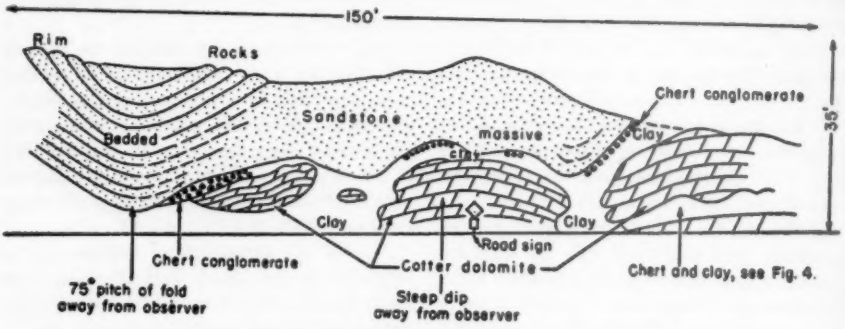


FIGURE 2.—DIAGRAM OF PART OF OTTERVILLE STRUCTURE

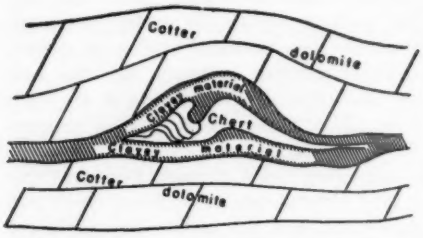


FIGURE 3.—"DRAGFOLD" IN OTTERVILLE STRUCTURE

Compare Pl. 2, fig. 1.

Otterville Structure

There is no better showing of a filled-sink structure in Missouri than the one in Cooper County, 3 miles east of Otterville (Fig. 2. *See also* Kansas Geological Society, 1941, Fig. 3). A road cut several hundred feet long and up to 35 feet deep has been made in the marginal part of a sandstone-filled sink (Sec. 35, T. 46 N., R. 19 W., Fig. 1, Ov). The nearly vertical walls of the cut are in rock sufficiently indurated to maintain a good exposure for many years to come. The Cotter dolomite constitutes the bottom and walls of the structure and a sandstone, presumably the St. Peter, makes the fill. Exceptional is the exposure of a part of the bottom of a sink!

The dolomite and sandstone dip back into part of this structure lies north of the highway and the cut along the road provides only a chord section. The minor foldings, whereby the Cotter appears in two anticlines beneath the sandstone, are radial corrugations comparable to the wrinkling of wet newspaper forced down into a funnel or bowl container, except that here the container also is wrinkled. A second mass of subsided sandstone, lying farther to the right and out of the diagram, completes the defining of a third anticlinal corrugation of Cotter. If the sandstone projected as a knob above the surroundings, it would qualify as a "blossom rock."

A chert conglomerate lies at the base of the sandstone, probably a basal conglomerate as the Kansas Geological Society's road log describes it. Below that, and locally penetrating into the Cotter dolomite, is a greenish clay with cherts; according to the road log "residual clay formed from the weathering of the underlying dolomite." "Weathering" is acceptable to the present writer only if here defined as decomposition below the surface, beneath the sandstone, and subsequent to the making of the basal conglomerate. The evidence supporting this is the lateral penetration of a part of the clay seam into the lower exposed part of the Cotter just east of the sandstone. A definite upbulge of a few feet contains a central cherty unit, enclosed above and below by blue-

green and brown clayey material in a minor asymmetrical anticline (Pl. 2, fig. 1). The central chert is definitely folded and sheared (Pl. 2, fig. 2). It can hardly be denied to be a deformation made under compression. Its asymmetry approximates that of a drag fold and the drag has been *out* of the larger structure, not into it. If it is a drag fold, the overlying dolomite has been pushed away from the sink center, and this could occur only if the structure is a compressional syncline instead of a sink, or if the subsiding sandstone mass in the sink had behaved locally as a wedge, not a purely fanciful idea. Another structure (Simpson coal mine) has irrefutable evidence that such outward-directed stresses have existed in Missouri's filled sinks.

The Cotter dolomite on the south side of the highway has a fine display of slickolite markings. Slickolites are essentially slickensides, but are not abrasional in origin. They are made by differential solution along minor fault planes in calcareous rock and repeatedly are accompanied by other evidence of displacement. They consist of alternating grooves and ridges or half columns which fit into ridges and grooves opposite them, the series on one face being the exact reverse of the marking on the opposite face. Ends of columns are engaged by sockets in the termini of grooves, and the column-socket relationship on one face is the opposite of that in the other. Thus the relative movement is recorded. Beyond any reasonable doubt, they are pressure-solution phenomena (Pl. 3, fig. 1; Pl. 4, fig. 2). They are known in calcareous rocks that have been diastrophically displaced but appear to be a far more common accompaniment of solution-subsidence. These engravings almost everywhere lie parallel to the steepest dip of the surface bearing them, as befits gravity-fault slickensides. They have never previously been reported from the Missouri filled-sink structures. The relative movement in the Otterville road cut was down to the north, toward the center of the structure. The strike of the surface bearing them is at right angles to the steepest dip of the sandstone and dolomite, or tangent to the margin of the structure.

A few hundred feet south of the highway, subparallel with it but at a lower level, is an even longer cut for the Missouri Pacific Railroad road bed, all in dolomite except for one intercalated sandstone lens. The rock has many warpings, some rather sharp, but no outline of the sink structure and no northward pitch such as that shown along the highway. Seeing this section alone, one would think only of the vagaries of interstratal solution and settlement. If these deformations are related to the sink, they must have been made in the floor rock well below the base of the sandstone fill.

The Kansas Geological Society's Guidebook (1941) posed two questions: "(1) Was the sand deposited in an existing sink-hole? (2) Was the sand laid down on an uneven surface and then dropped into its present position by the collapse of an underlying cavern roof?" The writer would add two more: (3) Is the sandstone a deformed mass of the presumed St. Peter or has it been re-worked and re-deposited? (4) Was the sandstone let down gradually as the underlying Cotter was unequally dissolved way (and concomitantly deformed)?

(1) Unless one is willing to accept subsequent deformation so great that any original sink outline has totally disappeared, the answer to the first question is "No".

(2) The basal chert conglomerate is a fairly uniform, thin sheet of gravel which required a fairly uniform surface for its deposition. Had it been deposited on such an uneven surface as the Cotter beneath now has, it would have been thicker in the hollows of that surface. We may consider the dolomite shown as part of the fallen roof rock, the collapsed cavern being below highway grade, but this deformed Cotter could never obtain its three anticlinal flexures and its folded, sheared chert through tensional fracturing and falling of cavern roof rock, therefore the theoretical cavern existed between a sandstone roof and a dolomite floor and the collapsed cave must lie before us in the section. Its "collapsed" roof subsided without sufficient free fragmentation to provide a cave breccia of rotated blocks. It came down gradually, even the basal conglomerate (the "cave" roof) maintaining its continuity; the pitching synclinal structure and the diverging rim rock outcrops testifying to subsidence *in toto*. There is no evidence in the exposures to suggest that an open cave ever existed here.

(3) The literature contains the idea that the sandstone fills of Missouri sink structures may

have been re-worked and re-deposited in later sinks and caves. Indeed, the blossom rocks have been called "fossil caves" (Fowke 1922). Nothing in the Otterville structure along Highway 50 remotely suggests that this is the correct explanation.

ory County, (W. ½ sec. 12, T. 36 N., R. 24 W., Fig. 1 Wb) is a cut 350 feet long and 12 to 15 deep in a Pennsylvanian shale and sandstone filling of what appears to be a sink cavity in Burlington limestone. The deformed sandstone shows an excellent example of an over-

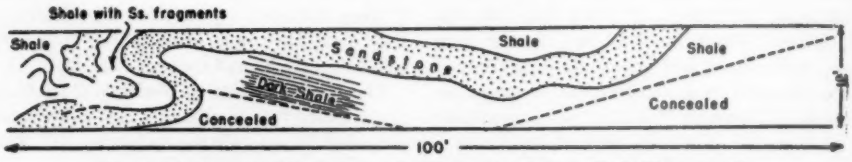


FIGURE 4.—PART OF WEAUBLEAU STRUCTURE IN CUT OF U. S. HIGHWAY 54

Strike of fold is about 45° to plane of section. Strata dip about 20° toward observer.

(4) The sandstone has suffered deformation without brecciation. So has the basal conglomerate. The clay with cherts is residual from solution of Cotter dolomite whose removal from beneath the sandstone has allowed the subsidence. The slickolites are explicable only by the fourth hypothesis. The deformations in the dolomite are due to the same solution that let down the sandstone. It was interstratal in making the downbend of edges adjacent to the clay pockets, and it probably was joint-determined where the clay cuts across the strata and penetrates down into the dolomite. The so-called drag folding seems to be explained only by lateral thrust out toward the dolomite wall on the east. Compressional stresses, not tensional, were involved throughout the making of this structure.

A small cave, partially collapsed, is shown in the section along the railroad, its roof broken to make two in-dipping slabs, otherwise an open cavity. With no fill above or below the broken roof, with no downbending in the wall strata and no associated clay with cherts, it obviously has no genetic relation to the Otterville sink structure.

Weaubleau Structure

Along the grade of U. S. Highway 54, in the eastern part of the town of Weaubleau, Hickory County, (W. ½ sec. 12, T. 36 N., R. 24 W., Fig. 1 Wb) is a cut 350 feet long and 12 to 15 deep in a Pennsylvanian shale and sandstone filling of what appears to be a sink cavity in Burlington limestone. The deformed sandstone shows an excellent example of an overturned fold. The sandstone will remain well exposed for a long time, but the structure of the shale is already considerably obscured and in places in Figure 4 the contact of sandstone and shale was approximated. The reverse fold will be admitted as such by any geologist who looks at it. Less clear is the interpretation of the isolated sandstone block, in the upper left of this figure, as squeezed completely through in two places but welded at the bottom to the S-folded sandstone stratum.

Although this fold of sandstone and shale is properly oriented on the valley slope to be the result of hillside creep, it cannot be such because a buttress of Burlington limestone crops out at the downhill (eastern) end of the section. The folding has been against that buttress. Some of the limestone dips 45° toward the folded sandstone, and vertical slickolites in it record internal movements accompanied by solution. The Burlington is wall rock that has shared in the deformation, slowly dragged down by the subsiding fill.

The general strike at Weaubleau is about 45° to the orientation of the highway but, like the Highway 50 cut east of Otterville, the structure here changes notably in the width of the cut. If the reverse fold on the south side continues across the highway width, it pitches below the grade. The Burlington on one side dips 45°, its

PLATE 1.—FOLDED STRATA IN SINK FILLS

FIGURE 1.—DEFORMED STRATA IN "FLOATING" LIMESTONE BLOCK, SIMPSON COAL MINE
The beds are bent through almost 90° of arc.

FIGURE 2.—THICKENED AND THINNED CLAY STRATA, HARBISON-WALKER PIT, LANE'S PRAIRIE

FIGURE 3.—CURVILINEAR WALL OF VERTICAL SANDSTONE, MOSELLE NO. 10 MINE

FIGURE 1

FIGURE 2

FIGURE 3

FOLDED STRATA IN SINK FILLS

FIGURE 1

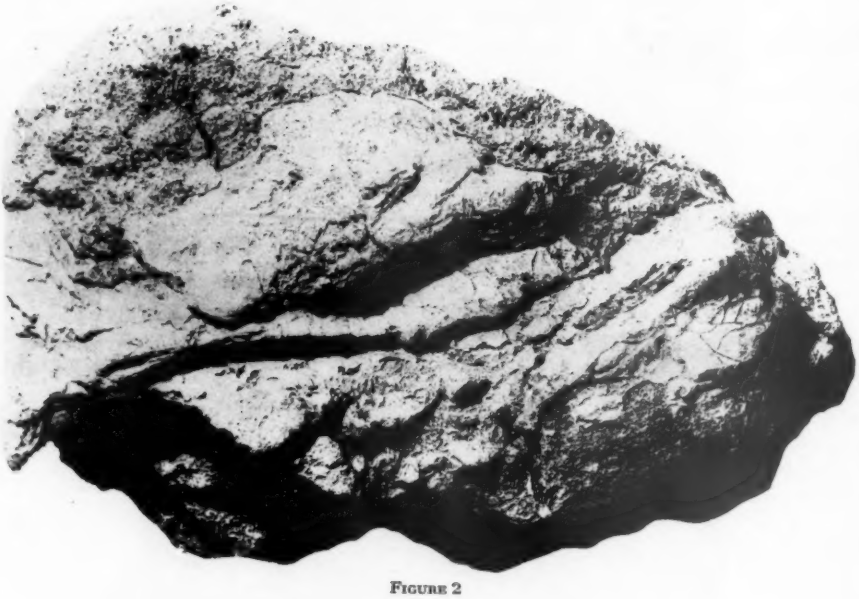


FIGURE 2

DRAG FOLDING IN SINK FILLS

continuation on the opposite side lies nearly horizontal. In the entire length of the cut, no particular element of structure on either side can be identified across the roadway.

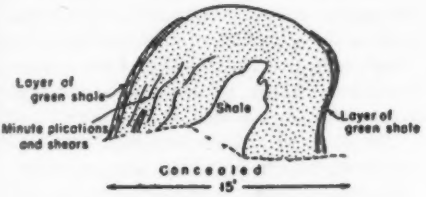


FIGURE 5.—WESTERN PART OF WEAUBLEAU STRUCTURE

South side of cut of U. S. Highway 54.

At the west end of the cut and only on the south side of the highway is a huge projecting mass of sandstone very deformed and largely lacking in surviving stratification. The interpretation (Fig. 5) as an isoclinal fold is based on a thin green shale layer bounding the two sides of the mass, a core of shale apparently infolded in the central lower part and minor wrinkling and shearing in one flank of the fold.

Pronounced lateral squeezing seems to have occurred at each end of the cut. The S-fold is close to the wall rock on the east and presumably the isoclinal fold is similarly close on the west. Deformation of both shale and sandstone is considerably less in the central part of the exposure.

The strongly marked compressional structures in the Weaubleau section decide immediately that Weaubleau is not a sink hole fill nor a cavern collapse. It may be a diastrophic structure, for much faulting is known in this district (E. L. Clark, personal communication). But, if so, solution-subsidence has been superimposed, the failures developing slowly enough and under sufficient load to maintain a stratal continuity through the entire deformation. The maximum load above the site of this structure cannot have exceeded 1000 feet of Pennsylvanian sediments. Probably 250 feet would be a more reasonable maximum. Solutional removal of Burlington limestone some hundreds of feet down in the phreatic zone, without open cavity making, produced the slowly applied stresses.

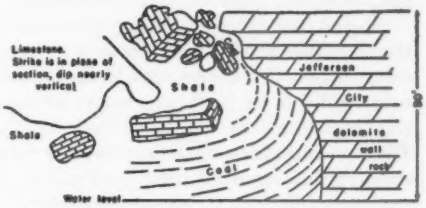


FIGURE 6.—BURLINGTON LIMESTONE BLOCKS "FLOATING" IN COAL AND SHALE

North wall of Simpson coal mine.

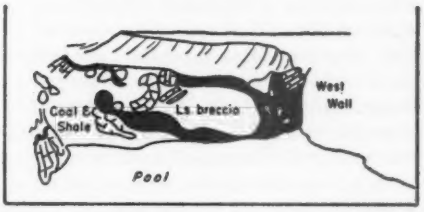


FIGURE 7.—COAL, SHALE, AND LIMESTONE BRECCIA

South wall of Simpson coal mine.

Subsidence between downward-converging walls caused the folding.

Simpson Coal Mine

The abandoned pit at Simpson Coal Mine, 2 miles east of Excelsior, in Moniteau County, (W ½ sec. 15, T. 43 N., R. 16 W., Fig. 1, Ss) measures about 300 by 500 feet; its walls descend very steeply for 50 feet to the surface of the pool now occupying the bottom. One instantly recognizes that the excavation is in a breccia of big blocks of white limestone embedded in a black shale and coal matrix (Figs. 6, 7). Only a small part of the wall shows the container rock *in situ*. Blocks range up to 50 feet in exposed diameter. All have been rotated. Their strata dip in every direction and at every angle. Prevailingly the strikes in the larger blocks are tangent to the periphery of the pit and in perhaps half of all the larger blocks bedding dips gently out of the pit.

PLATE 2.—DRAG FOLDING IN SINK FILLS

FIGURE 1.—"DRAGFOLD" IN OTTERVILLE STRUCTURE

Compare fig. 3.

FIGURE 2.—FOLDED AND SHEARED CHERT FROM "DRAGFOLD" IN OTTERVILLE STRUCTURE

The blocks are of Burlington, Chouteau, and Sedalia limestones, the wall rock is Jefferson City or slightly higher Ordovician dolomite and the matrix, of course, is Pennsylvanian.

Some of the limestone blocks are warped, their stratification curving notably through many degrees of arc. One such block is vertically bedded in its basal part, nearly horizontally bedded in the top part (Pl. 1, fig. 1). The vertical bedding terminates beneath in a truncated face against a bed of gently dipping cannel coal. The internal deformation, whereby the limestone blocks were bent, is repeatedly recorded by slickolite partings; some parallel to the bedding, most of them steeply inclined and indicating a downward displacement of that part of the block nearest the center of the sink structure. Most intriguing are bedding plane slickolites in some large blocks on the eastern side of the pit. The stratification in these blocks dips somewhat toward the wall. The solutionally impressed markings occur on both top and bottom of a given stratum but, instead of lying in the bedding plane (or at right angles to it), they stand with a steeper angle than the dip and their column and socket relations are such that only an outward thrusting of the superjacent layer over the one in question, and an outward thrusting of this layer over the one beneath could have made the markings (Pl. 3, fig. 1). They appear to be a resultant of two directions of thrusts, down into the sink under gravity and laterally because of solutional widening of the sink during the deepening.

Another striking feature of the Burlington blocks is the occurrence of small fragments of cannel coal actually pushed into the limestone, space having been made by solution of the limestone back of the coal fragment (Pl. 3, fig. 2). If a piece of the coal is extracted, there remains a cavity exactly the shape of the coal fragment. Some of these cavities have striated sides, orientation of striae being the direction the coal has been moved to present position. The coal pieces do not show internal slickensides although only pressure-solution can explain their position.

Crystals and crystalline aggregates of galena and sphalerite also occur partially embedded in the limestone, though rarely as deeply as the coal. The sides of some pockets containing them are striated. One sphalerite crystal itself was striated appropriately for this pressure-solution mode of emplacement.

There are slickolite markings also on the surface of limestone blocks, obviously made by movement between contiguous masses of limestone and coal. Most of these markings are steeply oriented. No stylolites of the conventional long, straight, columnar Burlington type, perpendicular to the bedding, were seen.

The coal and carbonaceous shale structures repeatedly have their laminae wrapped around the limestone blocks, to fit every detail of block contours. In places it seems doubtful that this is deformed stratification for the layering contains chert fragments and limestone fragments, and the coal is a breccia. In most places, however, with little question, the structure is true stratification and stratified coal underlies the Burlington masses. Coal also occurs as small dikes thrust into cracks in limestone and chert, and for as much as 2 feet along bedding planes in the Burlingron blocks. There seems to be a layered or laminated structure in these bedding plane dikes. The reverse relation, thin limestone seams in coal, does not occur.

There is almost as marked continuity of coal and shale bodies in the walls of this excavation as there is isolation of limestone masses. Though great quantities of limestone were taken out of the central part, as the dumps testify, exploitation of the deposit stopped as the bedrock walls were approached, obviously because of an increasing proportion of limestone. With greater depth the amount of coal became less but sphalerite more abundant until the Simpson was being operated as a zinc mine, with coal only an accessory product. Mining was discontinued when, at a depth of 150 feet, the zinc sulfide content of the mass of boulders in shale dropped below a profitable yield (E. L. Clark, personal communication).

The north wall of the pit (Fig. 6) has the largest coal body now shown. In part, it underlies an overhanging wall of Jefferson City dolomite *in situ*. The overhang is interpreted as the result of somewhat greater solutional removal of wallrock immediately below. The lower half of this section is coal and shale without limestone fragments. The stratification is nearly horizontal in the center but is tilted up at increasingly steep angles nearer the wall rock

and higher in the section until verticality is attained.[2] This structural relation surely is drag from subsidence, without fracturing, of the coal and shale. If deepening of the sink continued for a longer time than did widening, or was more rapid in closing stages, the down-dragged coal and shale found the overhanging wall already existing. Nevertheless, there must have been a horizontal component in the subsidence to thrust the shale and coal under the overhang after it had been passed.

The country surrounding the Simpson coal mine structure is underlain by the Jefferson City formation and perhaps still higher Ordovician dolomites. Some miles to the north is the southern edge of the Mississippian cover, unconformably lying on the Ordovician. The sink's filling of Pennsylvanian and Mississippian rocks had to be secured from a former cover of both, a cover that was stripped off later during the Ozark peneplanation. Much of the sink-making, therefore, must be dated at least as far back as earlier stages of that erosion cycle.

The pit was excavated at least 100 feet below the bottom of near-by Burris Creek valley, yet the mine produced insufficient water to run the zinc mill and the surface of the pool standing in the excavation today is determined by surface runoff (E. L. Clark, personal communication). The remaining shale does not constitute a complete seal of the wall rock. This rock, exposed for full depth at the north end of the pit, must therefore have a very low permeability and must lack the minor solution channels which are commonly associated with larger caves. Although yielding little water, this 100 feet of Jefferson City dolomite below creek level can hardly be considered in the vadose zone.

The water table, or lower limit of air in interstices, has never been lower in the rock than it is today. It has been lowering at the site of the sink, progressively down through the Cherokee Pennsylvanian, then down through Mississippian strata and finally down into the Ordovician formations. The lowest 100 feet of this solution cavity has never been above the phreatic zone and was therefore made in that zone. Because the present cycle of erosion has lowered the water table 150 feet below peneplain traces in the region, and the sink is pre-peneplain in origin, the lowest 250 feet of original depth must have been made in the zone of complete saturation.

It seems clear that, despite the sapropelitic character of the coal, the Simpson deposit cannot record a swamp in its pre-Pennsylvanian sink hole. If ever such a feature existed here, its bottom was far above what remains of its subsided fill. The hypothesis for filled sinks most favored in the literature, however, is that of cavern collapse, but several authors admit that the cave breccia may have later gone deeper by operation of the mechanism favored in this paper for the entire sink-making.

If a cave once existed here, it may be thought of as developed in the Jefferson City below the present sink bottom, simple tensional collapse accounting for all the structural and stratigraphic relations noted. A cave hundreds of feet below the water table of its time, possessing an extraordinary clear height between floor and ceiling and producing by its collapse a vertical subterranean "cliff" 150 feet high in the Jefferson City dolomite, must be postulated. One must also ignore those extraordinary structures of limestone block warpings, of slickolite orientations, of coal penetration into limestone and of coal dikes marginal to a central coal body which was undeformed by that fall of hundreds of feet.

There is no shred of evidence in the materials of the fill that a cave ever existed in the Burlington limestone. Even if it did, quite another mechanism took over directly beneath it to produce what we see, and no causal connection between a hypothetical cave and solution-subsidence beneath is apparent. Pressure-solution consequences of slowly applied compressive stresses are written in capital letters on the Simpson cavity fill, and this work was done far below the water table.

If not more than half the total thickness of Mississippian formations overlay the site and if the Cherokee thickness above that was not more than 50 feet, penetration to reach the top of the Ordovician dolomite was something like 300 feet. Add to that the 250 feet below the top

[2] Van Horn (1905) reported that the coal, dipping 45° at the north end of the pit, "becomes flat-lying" along an exploratory tunnel driven toward the center of the deposit at a depth of 99 feet. In 1912, according to Hinds, 45 feet of cannel coal was exposed in the flat-lying part, underlain by at least 40 feet of dark clay containing boulders of flint and limestone.

of the dolomite and we have a sink deeper than its length as now shown. Was this extraordinary penetration attained before the Ozark cycle stripped off the former Cherokee and Mississippian cover or did it continue through the peneplain-making cycle, and perhaps during the present cycle? Field evidences are scarce. The sink lies close to Burris Creek valley bottom, both vertically and horizontally. If subsidence went on during the making of the creek valley, the stream has inexplicably missed the weaker rock and lower altitude of the site of the sink. In all Missouri filled sinks, the subsidence seems to have come to an end at least by the time the peneplain was attained. If pressure was entirely from superincumbent load, the reason for cessation of deepening is obvious.

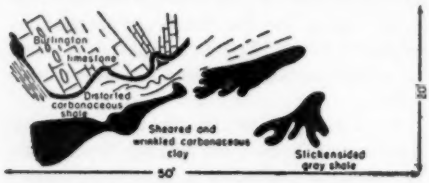


FIGURE 8.—DEFORMED COAL AND SHALE BENEATH TILTED BURLINGTON LIMESTONE BLOCKS

North wall of Midnight coal mine.

The Simpson pit has no sandstone in its fill, nor any marginal residual clay and cherts from solution of the Jefferson City dolomite walls. Basal Pennsylvanian sandstone may be thought of as having gone deeper than the limit of mining. Clay and chert residuum may also have been sheared off the walls and carried down out of sight. There is one stratified clastic coal bed, containing chert and limestone fragments and interbedded clay seams, near the top of the fill as now shown in the south wall. It may record an open-sink cavity, subsequent to the collapse, at some time during the erosional destruction of the upper part of the fill. Of similar origin may be a 6–10-foot deposit of residual soil mixed with cherts, lying on top of a settled block of Jefferson City in the southwest angle of the pit walls and 12 to 15 feet lower than the top of these walls nearby. All else in the filling of the structure has come down from 100 to 400 feet below its proper stratigraphic level.

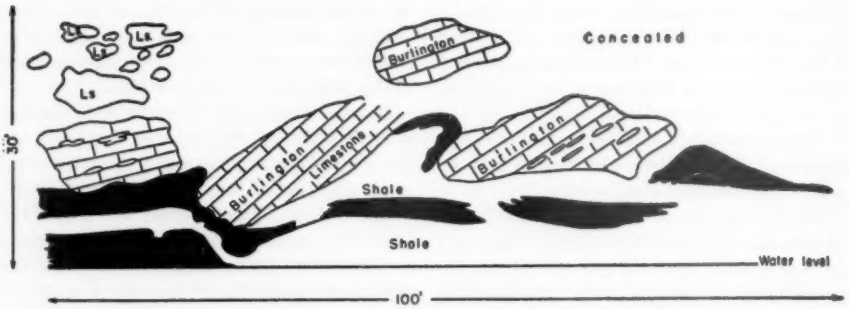


FIGURE 9.—DEFORMED COAL AND SHALE BENEATH TILTED BURLINGTON LIMESTONE BLOCKS

South wall of Midnight coal mine.

Midnight Coal Mine

No wall rock shows in this coal pit (SW ¼ of SW ¼ of sec. 26, T. 45 N., R. 20 W. Fig. 1, Mn) 3½ miles south of Smithton, in Pettis County; the material in the pit is Burlington, Chouteau, and Cooper limestone and Pennsylvanian sandstone, shale, and coal, intermixed in an intricate mosaic on the excavation walls. The deposit, where opened at the level of Brushy Creek's valley bottom, lies below the top of Ordovician dolomite outcrops near by. Its structure shows that much subsided rock must lie deeper.

Burlington limestone shows in isolated masses up to 25 or 30 feet in maximum exposed length, all resting in various tilted attitudes on Pennsylvanian sediments (Figs. 8 and 9). The larger blocks dip eastward. On the lower sides of most of them, the truncated strata edges rest on shale or coal with angular discordances up to 90°. An attractive idea is that these have toppled from now-vanished Burlington walls into a

sinkhole then being filled with Pennsylvanian clay and peat. The numerous striated faces of these blocks, plus the pronounced internal distortion of all the shale and coal and the deformation of their strata indicate that, even if this is correct, much subsequent subsidence has occurred in the sink. The limestone block in the north wall (Fig. 8) has itself suffered unequal solutional thinning of some layers and intrusion of shale along other bedding planes since it became embedded in the Pennsylvanian matrix. The former Mississippian cover at this place was at least 150 feet thick, probably considerably more. The deformed fill is not part of a Pennsylvanian deposit, as such, in a sink hole penetrating into the Jefferson City formation. The floor of any former doline or surface solution sink must have been well above present surfaces.

Burlington limestone, outcropping in Lake Creek valley, a mile to the east, has been broken into large masses which became somewhat tilted and then were recemented. Sulphurous springs in the bottom of Lake Creek valley near these outcrops suggest a body of Pennsylvanian pyritic shale and coal still deeper, and that another structure like Midnight has been entered by Lake Creek's downcutting.

The fairly continuous coal and shale masses under Burlington tilted blocks in the coal pit do not record a simple cavern collapse in Burlington horizons. If a former Burlington cave had been filled with the Pennsylvanian shale and coal, then both fill and walls collapsed by failure of an empty cave, directly beneath in the Jefferson City formation and considerably lower than present valley bottoms, conceivably the crowding and squeezing could be produced and the coal then could lie beneath Burlington masses. This is the essence of Pumpelly's (1886) explanation. Midnight does not afford the convincing evidence of slow subsidence that so many other such structures do. For either a cave or a solution-subsidence structure in the Jefferson City dolomite, however, one must admit adequate circulation of ground water in the saturated zone.

Above the intimate mixture of limestone blocks enveloped by deformed shale and coal

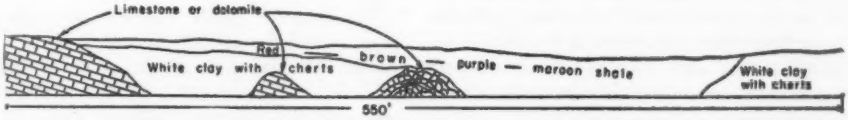


FIGURE 10.—PART OF SECTION ALONG NORTH SIDE OF U. S. HIGHWAY 50, A MILE NORTHEAST OF GRAY SUMMIT

is an overburden of clay and chert that appears to be slope waste of the present valley side. The fire that burned a vertical slot up through the largest coal body, coked the adjacent coal and clinkered the clay and chert overburden, occurred late in the present erosion cycle, after the water table had been lowered to its present position, long after subsidence had ceased.

Gray Summit Structures

There are three sections in the vicinity of Gray Summit, Franklin County, of interest to students of filled-sink structures (Fig. 1, G). A cut for the grade of U. S. Highway 50, a mile northeast of the town, shows a congeries of limestone masses, clays with chert, and red to maroon to brown shales, all with disordered structures and all lower than their proper stratigraphic levels. Two cuts along the Missouri Pacific railroad even closer to the town show a large mass of St. Peter sandstone down in the Jefferson City dolomite and a simple cave failure with no attendant downward intrusion of younger Paleozoic rocks.

The section along the highway is being obliterated by slump, slope wash, and vegetation, and contacts are particularly difficult to see. Big masses of the different lithologic units, however, will continue to show for years (Fig. 10). The three units of calcareous rock are light-brown, fine-grained, well-bedded, and non-cherty. They apparently are part of the subsided fill, not floor or wall rock. The structureless mass of whitish clay-with-cherts contains corroded fragments of dolomite or limestone and is interpreted as residuum from such rock, decomposition having occurred in

the sink structure beneath the strongly colored shales. The cherts are punky and semi-tripolitic. The underlying brown limestone or dolomite, however, was not the source rock.

Dips toward the structure's center and subsidence below the bottom of the cut are clearly on record, also a lateral crowding that made one of the calcareous masses into a fractured anticline. The shale undoubtedly is Pennsylvanian. It has smutty seams here and there and some intercalated brown chert gravel that looks worn and probably has been sorted.

At the eastern end of this section are small outcrops of a white crystalline limestone, its structure not obvious and its contacts not shown. It was not included in the diagram. It looks like Burlington lithologically but was not definitely identified.

As in all road and railroad sections through filled-sink structures, the details change across the width as well as the length of the cut. The south side, however, shows the brown limestone or dolomite, the residual clay-with-cherts, and the white, crystalline limestone. The colored shales are much less in evidence, and the sink center is therefore presumed to lie north of the highway.

Every exposed mass of limestone or dolomite possesses slickolite markings, steeply oriented and essentially small fault planes (Pl. 4, fig. 2). They also exist at the contact between clay-with-cherts and the limestone or dolomite, but because the adjacent rock is not calcareous, they are not duplicated on the opposite face.

The sink structure lies in a belt of St. Peter outcrops, yet no sandstone was found in either side of this long cut. No wallrock is shown. St. Peter undoubtedly has subsided into the underlying dolomite, the local solution of which probably has made the subsidence structure.

If Pennsylvanian sediments have come to the stratigraphic position of the St. Peter and St. Peter has disappeared into the Jefferson City below, the minimum depth of penetration would be the sum total thicknesses of St. Peter and higher Ordovician formations and of Mississippian formations in this district.

This Highway 50 section near Gray Summit records mostly vertical displacement. It clearly does not represent a fill made in a pre-St. Peter sink hole. The slickolites and the clay-with-cherts show that it is not a cavern-collapse structure, but must be the product of slow subsidence into a localized solution cavity. Residual clay-with-chert in these structures has been correctly interpreted by several authors who overlooked its implications. Credit for the correct understanding of such structures' origin appears to belong to Marbut (1907).

The Missouri Pacific railroad has made a long, open-cut approach to both ends of its tunnel, 100 feet beneath the town of Gray Summit, through the divide between the Meramec and Missouri river drainage areas. Both cuts are in Jefferson City dolomite. Near the west end of the western cut, however, the continuous dolomite wall is interrupted for about 150 feet by a block of massive St. Peter sandstone extending the full depth of the cut, 30 or 40 feet. For 100 lineal feet, this sandstone constitutes a clean vertical wall. Junction with the Jefferson City at either end is somewhat obscured by broken rock and vegetation. The Jefferson City itself has only minor warpings, probably from interstratal solution and not related to the sandstone body. It shows no down-drag or definite thinning of strata close to the mass of St. Peter.

The sandstone strata, however, are tilted, bent, and broken. The dip at the west end is 65°, away from the adjacent Jefferson City dolomite. It becomes less toward the east but bedding is lost at the east end of the block in a series of steep, west-dipping joints, spaced a few inches to a few feet apart. Although no slickensides were found, these joints probably are shearings or minor faults due to a greater subsidence in the central part of the sandstone mass and frictional retardation of settlement in this marginal part. No brecciation or even slight rotation of the sliced blocks seems to have occurred; the sandstone apparently was a tight fit during its subsidence and did not fall to position into an open cavity in the dolomite.

If this sandstone mass projected above the surrounding Jefferson City and had no cut through it, it would resemble the "blossom rocks" of the Rolla region which Lee (1913) believed were former caves that became filled with detrital sand and now stand in relief because of superior resistance to erosion. Such projecting masses had been reported from Morgan County by Marbut (1907) who saw them as subsided, deformed masses of St. Peter

"brought to their present position by the solution of the underlying limestones and the settling of the sandstone into the solution cavities." This appears to be the correct explanation for the sandstone mass in Jefferson City dolomite at Gray Summit. There should be a lining

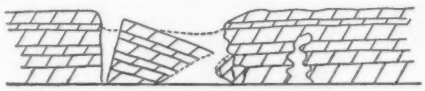


FIGURE 11.—COLLAPSED CAVE
GRAY SUMMIT

of the cavity with clay and chert residuum from the Jefferson City that has been removed in solution. Unfortunately the section is obscured where this would show.

In the railroad cut about 100 feet from the eastern portal of the tunnel is a section across the upper part of a collapsed cave (Fig. 11). A large tilted block of Jefferson City dolomite leans eastward into the former cavity and a smaller west-tilted block shows on the east side of the cave. Matching of strata across the gap left by the large block's tilting shows that no subsidence, other than the tilting, has occurred. The walls of the gap are as unmarked by solutional grooving on strata edges as are the walls of the railroad cut. The eastern side of the cave, however, has horizontal grooves and ridges determined by differences in solubility of the various strata and therefore is interpreted as surviving cave wall. The missing western wall has been tilted far enough over to become buried in the debris fill. The eastern and smaller block appears, from attempting to match strata, to have subsided 4 or 5 feet.

No roof of this former cave could have existed at the level of the top of the railroad cut when the large block became tilted. The top of the block apparently carries a tilted portion of the present bedrock surface. If this is correct, the cave had already been unroofed and the collapse is a late event in the present cycle of stream erosion and cave destruction throughout the Ozarks.

Closely adjacent is another cave chamber exposed by the railroad cut, a still-roofed vertical slot with wall moldings made by differential solution. It is taken to be another part of the same cave system.

Return of the in-tilted blocks of the collapsed cavity to their original positions would leave a solution chamber, wide at track level and narrowing upward into a similar vertical slot. The most capacious part of the old cave appears to have been below track level.

These cavities are, of course, wholly inadequate for a cavern collapse theory to account for the two solution-subsidence structures near by. There is no evidence that this particular cave collapse occurred beneath a cover of St. Peter and younger Paleozoics. The stresses indicated in its collapse were tensional. The cave itself is, in the writer's opinion, probably much younger than the sink structures. In an extensive acquaintance with Missouri caves, the writer has seen many cavern-collapse structures in them and in adjacent outside cliffs. Almost all show inadequate size, tensional failure, unfailed associated chambers or continuations of the one chamber, and lack of subsided masses from overlying formations. Brecciation is far better developed in most than at Gray Summit, and generally a roof still exists, the fracture-made cavity having migrated up in the rock as the solution-made cavity became filled. Where close to filled sinks, the contrasts show even more the different origin of Missouri's caves and filled sinks.

Macedonia Sections

Subsidence deformations in Pennsylvanian and Ordovician rocks are shown in several cuts along U. S. Highway 63 north of its junction with U. S. Highway 66. Two of these cuts, which promise to remain clean for years (Fig. 1, Ma), are named for the Macedonia church and school which stand near the highway and between the sections in Phelps County. Each section is on the crest of a hill in the highway grade and the best showing, in each, is on the west side of the road. The southern exposure is on the line between the southwest and southeast quarters of section 14, T. 38 N., R. 8 W. The northern one is in the southwest quarter of the southeast quarter of section 2, same township and range.

The southern section contains two down-bent sandstone members alternating with two members of white shale or clay (Fig. 12). The lower clay member is very cherty and is considered by Grawe and Cullison (1931) to represent the

upper Cotter or Powell dolomite. The sandstone beneath is basal Cotter and the overlying sandstone and shale are identified as Pennsylvanian. Although they call this a "sink structure", it cally, much the same kind of a pattern would be seen. The entire cut is presumably tangent to the periphery of a fairly large filled-sink structure whose main portion lies west of the

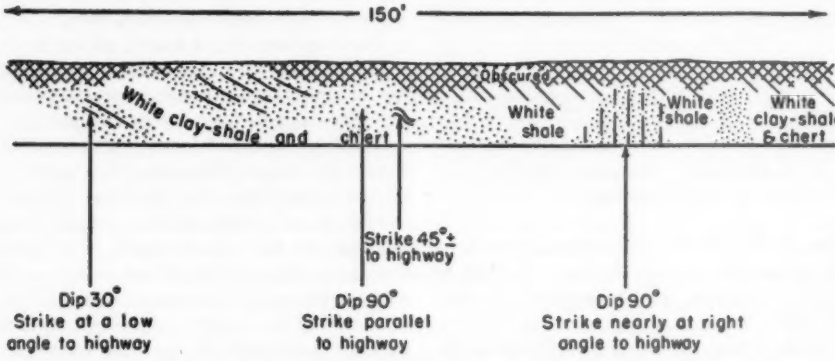


FIGURE 12.—SOUTHERN MACEDONIA SECTION ALONG U. S. HIGHWAY 63, NORTH OF ROLLA

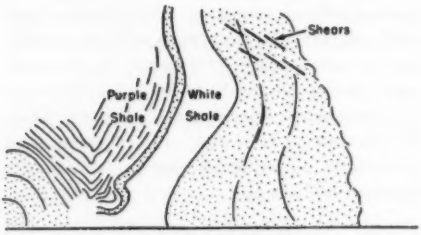


FIGURE 13.—DETAIL OF NORTHERN MACEDONIA SECTION ALONG U. S. HIGHWAY 63, NORTH OF ROLLA

does not fit Grawe's definition whicn is based entirely on wall rock. No wall rock is shown in contact with the fill structure. The nearest seen by the writer is 50 feet or so distant and on the opposite side of the road. Here it is flat-lying Jefferson City dolomite.

One significant structural feature, no cross-section diagram can show. The vertical beds at the north end of the section strike nearly at right angles to the highway, but this strike twists around through 90° to become parallel with the road in mid-length. The white clay-shale with cherts passes the mid-length portion under the highway ditch rather than beneath the sandstone. The structure is not that of linear folding as first glance would suggest. It is three-dimensional contortion. Were the section cut horizontally, instead of nearly vertiroad. The structures are interpreted as three-way undulations in a prevailing westward dip into an inverted cone.

Internal deformation of the sandstone is shown by thickening and thinning of layers and by quartzitified slickensides in the sandstone. In one place, parallel and steeply dipping slickened surfaces are repeated eight times in a thickness of about 6 inches of sandstone.

The northern Macedonia section, 2 miles distant, shows two projecting sandstone masses, limbs of a small syncline, with colored shale between. Both are presumably Pennsylvanian. The sandstone of the southern limb exhibits noteworthy thickening and thinning and possesses large corrugations on its under side, their lengths lying in the strike. Pockets of shale are thrust into the indented corrugations. On the upper surface are smaller corrugations with the same orientation and, superimposed on them, minute plications and little shear offsets, also elongated with the general strike of the mass. There are small quartzitified slickensided surfaces also, variously curved but all very steep and their striae directed down the slope.

The northern sandstone mass of this section apparently is itself a still smaller and a tighter syncline, containing squeezed and plicated shale. In the lower part of this shale is a thin sandstone layer, standing nearly vertical and bent (Fig. 13) to correspond with the bending

of the thicker sandstone stratum to the right, but pinched off at the bottom. Plate 6, fig. 1 shows a slab from this layer. The thicker sandstone has some shear partings, dipping northward out of the little fold. Two to six inches of conglomerate constitutes the basal part of the sandstone on both limbs of this sharp fold.

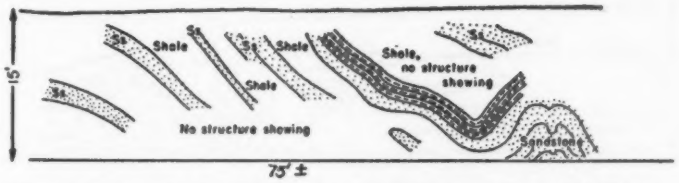


FIGURE 14.—EASTERN PART OF SECTION ALONG SOUTH SIDE OF EASTERN CUT OF U. S. HIGHWAY 50 ACROSS CAVE HILL RIDGE

Two hundred feet south of the prominent sandstone mass of this northern Macedonia section is an inconspicuous sandstone striking about east-west and dipping 30° to 45° northward. Westward into the woods on the hilltop, this strike leads in a few hundred feet to rim rock outcrops with northwest-southeast strike and northeast dip. With interruptions, this rim rock can be traced into a north-south strike and finally into a northeast-southwest strike, dipping easterly in all outcrops. With other sandstone outcrops east of the highway, the hilltop is outlined by patches of rim rock, most of them having a centripetal dip.

These two Macedonia sections record compressive stresses, applied slowly under confining load. The sandstones proved incompetent and behaved as have larger units in closely folded orogenic structures. They are impossible to explain by either the topographic sink-fill hypothesis or the cavern-collapse hypothesis. In the southern exposure, the cherty clay is the product of solutional alteration of original Cotter or Powell dolomite during the making of the structure.

Cave Hill Structure, Gasconade County

U. S. Highway 50 crosses a ridge between Second and Pinoak creeks, about 4 miles east of Mt. Sterling, Gasconade Co. and along its grade are three cuts (Fig. 1, CH) through such amazingly disturbed Pennsylvanian rocks that Figures 14–18 may be discounted by some as too largely subjective. The cuts[3], when the sketches were made, had been freshly cleaned by widening of highway shoulders and marginal ditching. Unfortunately there is so much shale

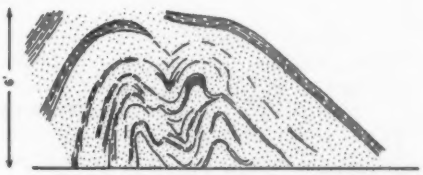


FIGURE 15.—DETAIL FROM FIGURE 14

in them that they are doomed to partial obliteration within a few years.

The highway utilizes a notch across the ridge, about 100 feet lower than the summit of Cave Hill, which is a part of the ridge crest just north of the road. The flat, wooded hill top is almost completely encircled by sandstone rim rock, the better exposures showing irregular centripetal dip and much local bending of the strata. By the criteria generally used, the hill should be the locus of a filled sink. The three clay pits at Cave Hill, however, lie down the slope, as much as 100 feet below this rim rock and outside its closure. The cave for which the hill is named is in subsided Pennsylvanian rock and also lies outside the rim rock outlining the hill top.

Structure of the south side of the eastern cut (Figs. 14, 16) is revealed almost entirely by the interbedded sandstone members; the shale generally is slumped and washed to produce a complete obscuring of its stratification. Although continuity is lacking in many places, these sandstones and shales clearly have been pushed laterally in the east-west plane of the section,

[3] The two eastern cuts are almost on the line between sections 11 and 14, T. 43 N., R. 6 W. The third cut is in NW 1/4 NE 1/4 sec. 15.

the thrust standing some strata on end, folding some into tight little anticlines and synclines, and displacing the folded rocks by faulting. As in other examples of filled-sink structures, Pennsylvanian sandstone and shale whose bedding in the large is not far from horizontal. Tortuous foldings of this sandstone and shale close to the quartzite near the top of the section

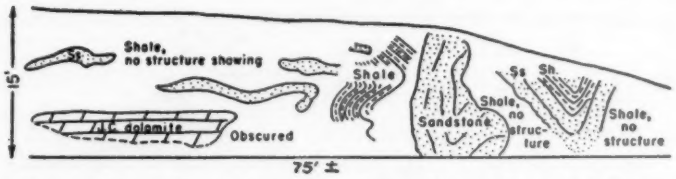


FIGURE 16.—WESTERN PART OF SECTION ALONG SOUTH SIDE OF EASTERN CUT OF U. S. HIGHWAY 50 ACROSS CAVE HILL RIDGE

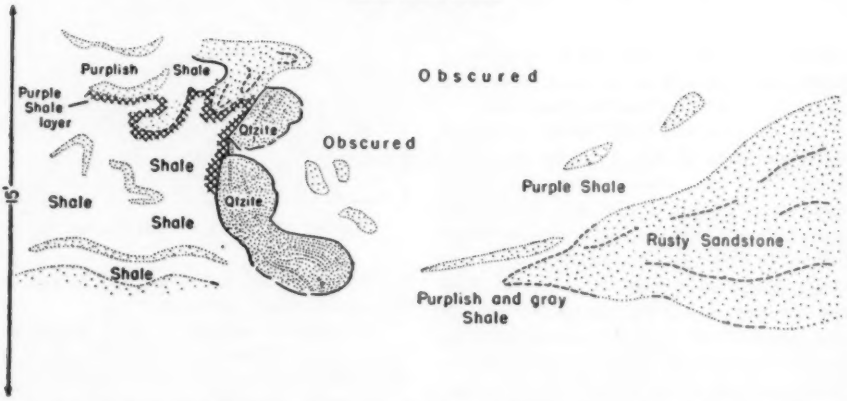


FIGURE 17.—DEVONIAN QUARTZITE EMBEDDED IN FOLDED PENNSYLVANIAN SANDSTONE AND SHALE

North side of eastern cut of U. S. Highway 50 across Cave Hill ridge.

the details of this cut cannot be traced across the width of the roadway. The deformations are not the linear foldings which the reader is likely to visualize from a glance at the drawings. Incompetency of sandstone members is shown, as in preceding instances. Small-scale foldings, with associated squeezings to sever some layers completely and to thicken and thin others, accompany the larger folds (Fig. 15). A block of Jefferson City dolomite shows also, but whether it is "floating" or a higher part of the floor is not known. This cut, not more than 400 feet long, is only a very small part of the structure of the southern slope of the hill.

Ulrich (see McQueen, 1943, p. 133 and 134) identified a white quartzitic sandstone member in this eastern cut as Devonian. It is considerably warped but stands almost vertically in the north wall of the cut (Fig. 17) flanked by indicate severe lateral thrusting from the west. One thinks of the quartzite as also deformed in that thrusting, being the steeper limb of an asymmetrical anticline, and of the poorly shown structure to the east as an accompanying syncline. An acceptable structural interpretation is that the white quartzitic sandstone is the same age as the rusty sandstone at the east end of the section. But if the quartzite is Devonian, it must be a slabby boulder of Devonian rock, incorporated in the Pennsylvanian sediments to lie parallel with their bedding (Bridge and Charles, 1922; McQueen, 1943). Because it lies in the shale and sandstone, it is not simply a larger fragment of a basal conglomerate.

The most challenging feature of the middle cut, also on the summit of the highway grade, is in its northern wall. The tilted and bent Jefferson City dolomite is cut from top to bot-

tom by a vertical body of downward-intruded, vari-colored shales. Gravity has pulled the green, white and purplish layers down into V shapes (Fig. 18) suggesting an isoclinal syncline. It has worked slowly enough to avoid breakage and brecciation, has literally stretched the shale broken surface possessing little offsets along fractures but no rotation of the pieces.

The three clay pits in Cave Hill environs show broadly deformed strata of Pennsylvanian gray clay from the Cheltenham formation with no associated masses of basal sandstone (Gray-

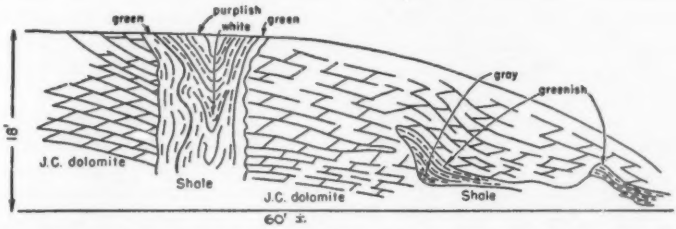


FIGURE 18.—PART OF SECTION ALONG NORTH SIDE OF MIDDLE CUT OF U. S. HIGHWAY 50 ACROSS CAVE HILL RIDGE

layers. The structure is impossible as a detrital fill in an open, vertically-walled sink or as a collapse filling of a subjacent cave. It could form only if concomitant solutional widening of the opening in Jefferson City dolomite were going on during the subsidence.

Interstratal solution seems the best explanation for much of the deformation in this Jefferson City block. If the gray and greenish shale shown to the right in Figure 18 is a lateral intrusion of Pennsylvanian, it is a product of the same mechanism.

On the south side of this middle highway cut is a large body of Jefferson City but little deformed. It may well be floor rock. The wall left by the highway engineers, largely a natural parting with the right location and orientation for their purposes, is one of the best slickensided limestone faces the writer has seen in Missouri filled sinks. The face is vertical and 30 to 40 feet long. The faulting is almost surely a part of the general filled-sink structure at the Cave Hill locality, striking peripherally to a deeper central area to the north.

The western cut, a minor exposure, shows tilted and folded sandstone masses like those farther east. The "folds" shown in Plate 6, figure 2 are really a series of local and alternating bulges in opposite directions. Stratification can be traced through the piece by thin layers with high percentages of chert fragments. One surface is a warped and broken bedding plane, the don) or of Jefferson City dolomite. The alteration of the original shale to burley refractory clay is further evidence that the pits are being dug into central parts of sink structures. Although the lowest exposures in Cave Hill, they possess the youngest rock shown.

Cave Hill's cave is the only cave known to the writer in any sink structure. The entrance to the cave is a ponor, a collapse sink hole, in the top of the ridge, about at highway level and nearly 1000 feet farther south. The walls of the ponor provide a good section 50 feet or so deep. The material shown is all Pennsylvanian shale and sandstone, as much as 150 feet below the top of the Jefferson City dolomite in adjacent hills. The sink's southern wall is a sheer cliff of sandstone for 40 feet down, with shale beneath. The other walls are shale almost throughout. The vertical contact between approximately horizontal shale and this mass of sandstone is certainly a fault. Drag crumpling at the contact indicates the sh .le to have gone down relatively. The shale has been highly contorted and squeezed in a minor way as though thrust against the buttressing sandstone.

The cave is usually full of water, reaching the low ceiling about 30 feet back in it. Apparently it has never been entered for more than 100 feet, even during drought. Since it is well up in a rather narrow ridge, this must mean a water-tight floor. The cave as shown is entirely in shale, and is therefore a collapse cavern. The

true solution cave beneath, in Jefferson City dolomite, has become filled with fallen shale and thus given a water-tight bottom.

The cave is post-subsidence. Had it existed earlier, it never could have survived the down-jamming, down-packing, down-crowding and down-squeezing which the Pennsylvanian rock has undergone. Failure today is by free fall from time to time of relatively small individual roof fragments and a subterranean talus slopes off into the deep water of the cave lake, normal procedure in most cave roof failure that the writer has seen. Nowhere, in some hundreds of caves studied, has he seen crumpling or other evidence of lateral compression in even the largest fallen roof masses.

That the solution cave existed before the sink structures were made, and survived the experiences recorded, therefore seems impossible. It is taken to be a later ground-water product, made under quite different conditions. The earlier mass failure and downward crowding of once-overlying Pennsylvanian rocks, now removed from hilltops of the region, occurred *pari passu* with an earlier solutional attack on the Jefferson City dolomite, no open caves ever being formed at that time and place.

If the idea of several closely spaced, even overlapping, subsidence structures at Cave Hill is in error and there is but one, it must be the largest known in Missouri. The hill top rim rocks, the highway sections, the ponor, the cave, and the clay pits are distributed over an area more than a quarter of a mile wide and nearly a mile long. Proponents of the cavern-collapse hypothesis will have less difficulty if they consider Cave Hill as a multiple structure.

Windyville Structure

The sections in a filled sink structure near Windyville, Dallas County, (S ½ sec. 5, T. 34 N., R. 18 W. Fig. 1, W) are only a few hillside ledges, a low cliff, and a bedrock stream floor. The exposures are in Gasconade horizons but the material showing is mostly sandstone and shale or clay. The deformations are on a small scale; no folds are more than a few feet in amplitude. In 1000 lineal feet of the cliff along the stream, probably not more than 50 stratigraphic feet are involved. No wall rock shows but the stream apparently is flowing on deformed floor rock for part of its course across the structure.

The low cliff shows interbedded sandstone and shale or clay, characterized throughout by thickening and thinning and minor crumpling. The stream bed over the edges of these folded sandstones is a series of pools and little cascades determined by the structures. Strikes are in virtually all directions. The corrugations show best on the bottoms of sandstone layers, with subjacent shaly or clayey layers. It is because of the remarkable uniformity of some of these wrinkles (Pl. 5) that the Windyville structure is discussed.

Specimens are fairly numerous although the better have been carried off as curiosities. Several of boulder size have been dragged up to a near-by barn. Because surfaces of the wrinkles are smoothed almost to a dull polish, and because of the straightness, parallelism, and uniformity of size, they have inevitably been considered an artificial product. Some of them resemble casts of ripple marks and one geologist has so interpreted them. If so, they have been considerably modified subsequently by lateral compression.

Their relief is too great and their grooves too narrow at the bottom to be original casts, and they have an asymmetry that may reverse between adjacent groups of ridges. Small wrinklings are superposed diagonally on larger. Many corrugated surfaces also show very acute-angled convergences and divergences of ridges

PLATE 3.—SOLUTIONAL DISPLACEMENTS

FIGURE 1.—SLAB FROM BLOCK OF BURLINGTON LIMESTONE, SIMPSON COAL MINE
The face of the slab is a bedding plane. The slickolites dip into it.

FIGURE 2.—PIECES OF CANNEL COAL IMPRESSED INTO BURLINGTON LIMESTONE

PLATE 4.—INTERNAL DEFORMATIONS IN LARGE BLOCKS IN SINK FILLS

FIGURE 1.—SHEARED SANDSTONE, SIMMONS MOUNTAIN HEMATITE MINE

FIGURE 2.—SLICKOLITES FROM FILLED SINK STRUCTURE ALONG U. S. HIGHWAY 50, NEAR GRAY SUMMIT

FIGURE 1

FIGURE 2

SOLUTIONAL DISPLACEMENTS

FIGURE 1

FIGURE 2

INTERNAL DEFORMATIONS IN LARGE BLOCKS IN SINK FILLS

FIGURE 1

FIGURE 2

BEDDING PLANE CORRUGATIONS

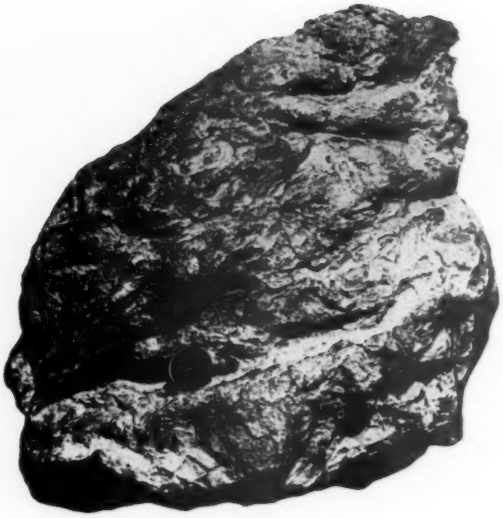


FIGURE 1

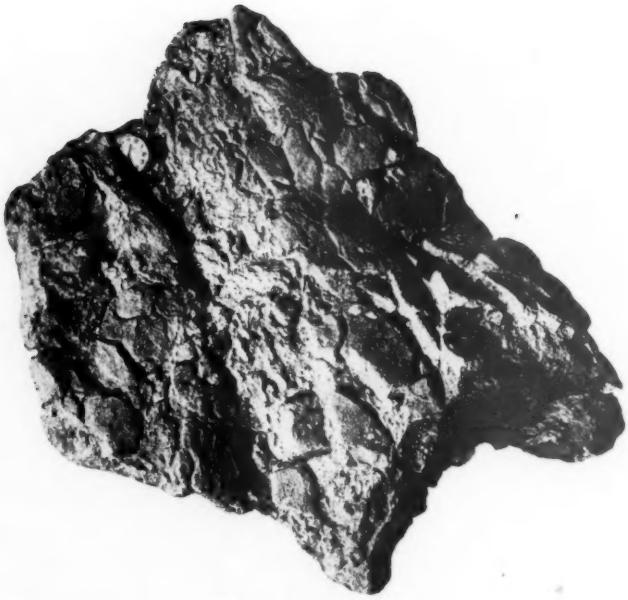


FIGURE 2

SQUEEZED SANDSTONE SLABS

and grooves. Those in place seem to occur on the bottom, not the top, of sandstone strata. If so, the hypothesis that they are modified ripple casts must start with ripples in the surface of the underlying shale or clay, and must accept the remarkable coincidence of lateral compression having been directed everywhere at right angles to the original ridges.

There has been much shearing also in the sandstone, making little offsets in bedding plane surfaces. The sand rock therefore was already consolidated when the deforming stresses occurred. These Windyville corrugations are of the same genesis as those reported in this paper from other filled-sink structures in Missouri. They are closely comparable with folded, corrugated, and sheared sandstone masses reported by the writer (1940) from a series of solution cavities in Silurian dolomite, filled with Pennsylvanian sediments, in northeastern Illinois.

Rueppele Hematite and Pyrites Mine

This mine, in Franklin County 2 miles west of Stanton (Sections 22 and 27, T. 41 N., R. 2 W., Fig. 1, R) yielded hematite for 15 years and pyrites for another 3 years. The original exploratory drill hole showed 64 feet of "broken rock and clay" overlying 126 feet of hematite, below which 40 feet of pyrites was penetrated. The mine was worked at seven different levels, an incline from the lowest level reaching a total depth of 333 feet. The lower limit of merchantable hematite was 268 feet below the surface. Pyrites mining followed exhaustion of the hematite, until difficulties with gas and fire from the rapid oxidation of iron sulfide finally caused abandonment.

The pit at the mine site, 500 feet long, 350 feet wide, and 95 feet deep, is due in part to an early effort to strip the overburden and in part to collapse of the old mine workings. Its eastern side is a great subsided block of massive sheared sandstone which, from associated vari-colored shales, is judged to be Pennsylvanian rather than the local Ordovician Roubidoux sandstone.[4] Its western side consists of large blocks of steeply dipping and variously tilted Jefferson City dolomite overlain by Pennsylvanian shales. Since the surface rock surrounding the pit is Roubidoux, the Rueppele pit apparently shows no true wall rock.

The sandstone on the eastern side of the pit has almost no stratification but many parallel and semi-parallel shear partings which dip steeply, most of them away from the center of the filled sink. The strikes are generally peripheral to the larger structure. Some broken surfaces of the sandstone are corrugated with ridges made by outcropping minor shears. This shearing in places apparently is minute faulting and asymmetrical folding. There are some larger faults also, with excellent slickensides and quartzitification. Since they do not conform to the pattern of the minor deformations, they may be records of movements between larger blocks of the subsided sandstone mass.

White, maroon, and purple shale beneath the sandstone is intimately slickensided. Almost every fracture shows smooth glistening surfaces. The bottom of the sandstone has corrugations elongated approximately with the strike of the dipping beds. In places, they suggest ripple

[4] Grawe (1945), from whose report the above data are taken, said that the sandstone block had "subsided into the pit" and that "the present dips of the rocks in the walls of the pit do not represent conditions prior to mining". The writer is convinced that the making of the pit has only revealed detailed structures and relations already existing in the filled sink.

PLATE 5.—BEDDING PLANE CORRUGATIONS

FIGURE 1.—CORRUGATED SURFACE OF SANDSTONE SLAB, WINDYVILLE

FIGURE 2.—CORRUGATED SURFACE OF SANDSTONE SLAB, WINDYVILLE

PLATE 6.—SQUEEZED SANDSTONE SLABS

FIGURE 1.—SLAB FROM THIN LAYER OF SANDSTONE; SQUEEZED AND CORRUGATED BETWEEN TWO SHALE MEMBERS

The infolds contain tightly wedged shale below bottoms of the grooves as shown. Northern Macedonia section on U. S. Highway 63

FIGURE 2.—BEDDING SLAB OF SANDSTONE; THICKENED, THINNED, FOLDED AND FRACTURED BETWEEN TWO SHALE MEMBERS

Western cut of U. S. Highway 50 across Cave Hill ridge

marks. Were they such, they would necessarily be casts of ripples in the shale. The internal deformation of this shale below the sandstone makes it clear that the corrugations are deformations.

One sandstone member of the shale, 12–18 inches thick and bounded by white shale on one side and purple on the other, is readily traceable through a drag fold 15 feet long and nearly 3 feet in amplitude. The movement producing this drag was neither down into the structure nor up out of it. Apparently the deformation at this place was produced by differential settling of large adjacent blocks of sandstone which lay above the shale.

Another sandstone layer, 6 inches thick, possesses a close similitude to chevron folds, each wrinkle asymmetrical like a drag fold. Only adequate pressure from the bounding shale and adequately slow movement prevented brecciation of this deformed sandstone layer. No tensional stresses of collapse into a subjacent open cavity could have done this.

Elsewhere, sandstone layers in the shale have been squeezed into a fair imitation of the boudinage exhibited by thin quartzite layers in a schist. The relative competence of the contrasted rocks of the two cases has been very similar.

The jostled blocks of the Jefferson City dolomite on the west side show no internal deformations and no surface markings resulting from movement. They all possess solutional rounding of outlines and solutional pockets indenting them. Apparently the dolomite yielded, where required by the differential pressures, by going into solution.

The abundant shear partings and the quartzitified slickensided surfaces in the Pennsylvanian subsided blocks; the corrugations at the contact of sandstone and shale; the drag and chevron folding in unbrecciated sandstone layers enclosed in shale; and the squeezed outlines of such layers all testify to the existence of adequate load and the occurrence of slow movement at the time this filled-sink structure was made. There is no evidence that an open cave existed beneath to receive the iron oxide and sulfide. Replacement seems the only alternative explanation for the ore deposit.

A well less than 150 feet outside the structure has a static water level 158 feet above the lowest reported depth reached in mining. Pyrites below hematite was encountered at depths ranging from that of this well's static level to 42 feet lower, the percentage increasing in depth as that of hematite decreased. Thus, hematite production dropped in 1 year from 20,100 to 1743 tons, and pyrites production rose during the next year from 3958 to 12,512 tons. This appearance of sulfide ore at the water level and its increase with depth marks the vertical transition from oxidizing to reducing conditions below the water table. Even though the mine may have been dry, it penetrated into the phreatic zone. The well's static level marks the water table and neither interstitial air above nor dissolved air below had ever reached the lower levels attained in mining.

The land surface when the Pennsylvanian rocks still overlay the region was far above that of today and the entire structure as now existing must have developed below an early and much higher water table. Present-day valleys have no alluvial fills of consequence and, unless one hypothecates with Lee (1913, p. 69) a time of great aridity, oxidizing water in the ore cannot be dated earlier than the present cycle of erosion. The solution which made the Rueppele filled sink occurred under deep phreatic conditions. Lee's period of aridity was an invention demanded by his belief that caves are made above the water table.

Ore was mined as deep as the level of the Eminence formation and Grawe speculated that the structure may go down to the Potosi formation, 460 feet below the surface. By the popular hypothesis of cavern-collapse, the required original cave had a height equal to the stratigraphic thickness of the Jefferson City formation, plus an unknown part of the Pennsylvanian above and Roubidoux below. Three hundred feet is a low estimate. A cave 300 feet high and scarcely wider or longer than that is needed for the hypothesis, built without reference to the characters of existing caves of phreatic origin in the calcareous formations of the region.

The Rueppele iron mine is 6 miles southwest of the Anaconda clay and coal mine and about 150 feet higher. Both occur in gently sloping country dissected from the Ozark peneplain before the steep-sided modern valleys were eroded. Both lie on the upthrown side of the

Leasburg fault where almost all Pennsylvanian and Jefferson City cover was stripped off during the Ozark cycle. The two sinks should be products of the same time and the same conditions. (1945), however, provides ample evidence bearing on the origin of the structure and virtually denying the cavern-collapse interpretation he (and earlier Lee, 1913) advocated.

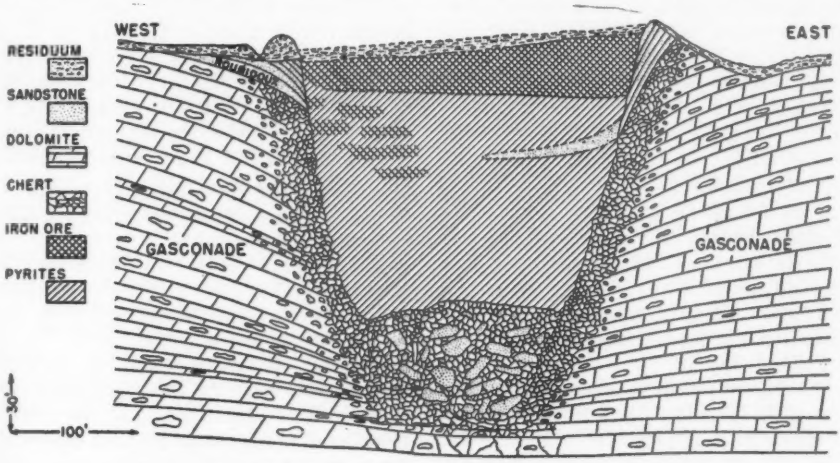


FIGURE 19.—DIAGRAM OF MOSELLE NO. 10 FILLED SINK STRUCTURE
After Grawe.

Yet Rueppele has yielded no fire clay or coal and Anaconda, no hematite, pyrites or masses of subsided Jefferson City dolomite. McQueen (1943) believed that a stratigraphic order exists in the Missouri sink fillings, iron ore underlying clay. Anaconda has lost more surface rock in post-peneplain time than has Rueppele. It should, by this view, be the iron-bearing sink and Rueppele should be the clay-filled sink. Only a small part of the difference in elevation is due to warping of the peneplain. May it not be that, because of an adequate pre-Pennsylvanian relief, the site of Rueppele stood high enough to escape burial in the clay and coal which covered a lower Anaconda site? May it not be that the clay and coal fill did not present favorable conditions for the postulated replacement of sandstone and dolomite that made the Rueppele deposit?

Moselle No. 10 Hematite and Pyrites Mine

The writer saw only the environs, the dump and the upper 30 feet of the pit wall of this abandoned water-filled mine in Phelps County 9 miles south of Rolla (Sec. 20, T. 36 N., R. 8 W., Fig. 1, Mo). Grawe's excellent description

At intervals between 1872 and 1934, hematite was mined at Moselle No. 10 in an open pit which grew to proportions of 200 feet by 90 feet horizontally and 32 feet deep. There was little overburden. At this depth, the ore was pyritic and from 1934 on, pyrites was mined to a finally attained depth of 185 feet. Below that, the structure contained pyrites for another 10 to 15 feet, beneath which exploratory holes found sandy and cherty pyritic material. The total thickness of the pyrites body was 140 to 150 feet. Wall rock was encountered, against which the pyrites deposit rather abruptly terminated, indicating a body of iron sulfide scarcely more than 250 feet in maximum diameter (Fig. 19).

The northern and northeastern wall now exposed above water in the pit is 25–30 feet high, composed of massive Roubidoux sandstone whose bedding stands almost vertical. This wall skirts about a quarter of the pit's circumference, and in ground plan is a continuous concave, bedding-determined wall (Pl.1, fig. 3). There is very little brecciation and little jointing. Some shearing and slickensiding exist. Information is that this face descends vertically

beneath the water. On it, above water, are broad, horizontally elongated corrugations. The vertical beds have been bent into their concave ground plan and the upper surface of the sandstone has become corrugated, all without prominent fracturing and without any rotation of units outlined by fracture.

Only internal yielding throughout the mass can explain such deformation. Indeed, the Roubidoux sandstone body is deformed through another curve, one in a vertical plane, for from this wall-like mass on edge, the rock is (or was) traceable out from the center of the structure to an abrupt decrease in dip to only 10° or 12° and thence, a few hundred feet from the mine, to dips of only 3° to 5°. This vertical curve is due to progressive thinning of subjacent Gasconade dolomite layers as the pyrite deposit is approached.

The character of the solutional attack which thinned the dolomite strata is well described by Grawe (1945, p. 392):

"The broad gentle sag is not confined to the sandstone but is present in the underlying strata as well. These now are clayey cherts which, by their tripolitic character and abnormal abundance, show evidence of the leaching which produced the sink structure. Irregular, wavy bedding planes observed along the pit walls also are highly suggestive of a differential compaction and subsidence of the area through solution of the cherty dolomite beds which once were nearly horizontal and extended across the area now occupied by the pit. The sandstone beds are bent down over the beds of chert."

No cave known to the writer shows anything approaching such conditions in its walls. Grawe added to his insistence on open caverns the saving statement that "the whole rock section was thinned and lowered by leaching of the carbonates, and a clayey, cherty residue was left in place of the original cherty dolomite. The residuum now forms the lower walls of the pit" (p. 391). He also said (p. 394) that "what may have been traces of bedding planes sometimes appeared in the working face" during the sulphur mining.

Discarding the idea of a cavern in the central part for replacement by sulfides during and after the making of the structure, these quoted statements give the thesis of the present study. Grawe, however, commented on the lack of evidence for replacement.[5]

Replacement by ore has penetrated locally into sink walls of three mines to produce a resemblance to ore-filled lateral cave chambers. Moselle No. 10 is one of these. In the most pronounced instance (Iron Ridge Mine), ore was followed for 130 feet back of the sandstone rim rock. Of this occurrence, Grawe (1945, p. 282) said that he "observed the ore in the adit in the southwest wall. It was earthy red hematite, interfingered with cherty clay and tripoli, and apparently it had replaced siliceous dolomite beds".

The pyrites body of the Moselle No. 10 mine contained a peculiar ledge of sandstone projecting like a semi-circular shelf from the eastern wall almost to the center of the pit (Fig. 19). Although specified as detached from the wall, it was not lower than the lowest of the in-dipping sandstone. It tapered from a thickness of 18 feet at the proximal margin to only a few feet at the distal end, and had a dip of 5°–10° into the pyrite deposit.

"Its top and bottom surfaces were somewhat irregular and cross-sections of it showed it to be highly fractured and sheared, especially at its eastern margin where it evidently had broken loose from that above and slipped down the eastern wall. Although the sandstone was fractured, it descended as a single mass. Fragments of sandstone were not scattered throughout the adjacent sulfide . . . "

The sandstone slab contained "numerous well developed pyrite cubes, some of which were a half inch on edge", and sand inclusions occurred in the crystals.

Grawe opined that the slab slowly settled through "water and the iron sulfide mud which was accumulating in the subterranean cavern." Water and mud never could transmit these shearing stresses. The shearing must record earlier conditions when there was a solid bottom and a solid top, all subsiding slowly together so that fragmentation of the surviving slab

[5] In Grawe's detailed description of pyrites mines and prospects in the filled-sink country, he listed 16 mines which exhibited some replacement by pyrite or hematite and 12 which have shown interbedding of ore with sandstone, clay, and chert. He accepted replacement of dolomite and sandstone as the whole cause for one hematite fill, the Christy.

was prevented. The slab is taken to be an unreplaced part of the subsided rock, for most of which the iron sulfide was later substituted.

The bottom of the pit is 65 feet lower than the near-by bottom of Gourd Creek valley. Obviously the water table has never been lower in the deposit than the bottom of the oxidized ore, and no vadose solution can have made this sulfide-filled cavity 150 feet deep in the Gasconade dolomite.

Grawe said (p. 183) that "the bowl-like shape of many deposits suggest that vadose water played the dominant role in the development of the structure. Its activity would be limited by the ground water surface, beneath which the rocks were saturated with water. As this surface was approached, the downward development of the cavity would be slowed up and ultimately stopped while, at the same time, lateral extension of the structure also would be limited."

He dated the sink cavities as pre-peneplain. Because no valleys of the pre-peneplain topography could have been lower in the rock than the base level of the finally-attained peneplain, and because many sink bottoms are some hundreds of feet lower than the near-by traces of the peneplain today, Grawe postulated a water table much too far below major valley bottoms, even of the present, to be credible.

If his water table was determined by major valley bottoms and his caves were of pre-peneplain vadose origin, the eventual peneplanation must have destroyed them all. The lowering land surface was constantly overtaking the lowering water table and the two were very close together at the culmination of the cycle.

If, however, his premise be granted, the full-grown vadose caves which were the predecessors of the filled sinks remained unchanged, with sandstone slabs projecting from walls and ceilings, until peneplanation was well along and the sulfide mud began to fill the cave. Not until then did these unstable features sag and break off and collapse in and on the mud. This sequence is difficult to accept.

Scarcely more than half a mile from Moselle No. 10 is Gourd Creek Cave, in the same rock as the filled sink. The cave possesses many features which date back to a phreatic origin. (Described in a forthcoming report of the Missouri Geological Survey). The filled sink and the cave have nothing in common, save that both are consequences of phreatic solution in the same formation. This long, narrow, low cave is typical of more than 100 caves known in the Gasconade formation of the Ozarks, its only unusual feature being a little gorge cut by a present-day vadose stream in the bedrock floor. Beyond a distance of about 500 feet from the entrance, one can traverse this cave only by crawling, although in so doing he may reach daylight on the far side of the ridge the cave underlies. No cave of such proportions and dimensions could conceivably have given origin, by collapse, to a filled sink of the size and ground plan of Moselle No. 10. Furthermore, there is no suggestion of interstratal solutional attack in the walls of this or any other cave the writer has seen in the Gasconade formation. Although both sink and cave antedate the Ozark peneplanation, the two solutional features are so different that we consider that different times and quite different conditions of phreatic ground water action produced them.

Cherry Valley Hematite and Pyrites Mines

These two mines, in Crawford County 5½ miles southeast of Steelville and less than a quarter of a mile apart (Sec. 4, T. 37 N., R. 3 W. Fig. 1, CV), have been the largest producers among all of Missouri's filled-sink hematite deposits. The western mine (No. 1) lies in the summit of a narrow ridge, the eastern one is about 80 feet lower at the confluence of two ravines. Mining, earlier for hematite and later for the deeper sulfide, has occurred at intervals since 1878. Much of this work has been open-pit mining, although underground methods have also been used. Nason (1892), Crane (1912), and Grawe (1945) have described and interpreted the geology shown at the times of their respective examinations. The writer twice visited the abandoned pits in 1946, once under the guidance of Dr. Grawe and Dr. Clark.

Cherry Valley No. 1 today shows as a pit about 450 by 250 feet horizontally and 80 feet in maximum depth. The pit of No. 2 is 900 feet long, 500 feet wide, and as much as 150

feet deep, largely filled with water. Each pit is surrounded by an interrupted rim rock of sandstone, and drilling has shown the area separating the two to be undisturbed, unmineralized country rock. The two mine locations therefore are not two collapsed portions of one original linear cave. The in-dip of the sandstone ledges steepens in conventional fashion, reaching and exceeding 45° nearer the pits. In one place in No. 1, this inclined sandstone shows today from top to bottom of the slope. No true wall rock of Gasconade dolomite appears ever to have been encountered in mining, the ore deposits being found to terminate against this sandstone lining of the cavities. Much of the pit slopes today are slidden clayey masses which lie within the sandstone margins. Some of this apparently is Pennsylvanian shale, not residual clay from once-overlying Jefferson City dolomite.

The rim rock and its downward continuation is strikingly brecciated in places where the dip is steepest. Yet rarely are the fragments so rotated and displaced that one cannot recognize original relative positions of adjacent pieces. In some there has been separation sufficient only to allow introduction of a thin body of matrix. The pieces are quartzite, the matrix is sandstone.

The hilltops of the region are capped with Roubidoux sandstone and most of the sandstone tilted toward and into the structures is undoubtedly from that formation. But one sandstone exposure on the northwest rim of No. 2 pit is thought by Grawe to be of Pennsylvanian age perhaps.

In the clayey debris of the slopes of No. 1 pit are boulder-sized, sheared sandstone fragments, their surfaces carrying little offset steps a quarter of an inch or so high. The subrounded outlines of the boulders do not appear to be directly determined by fracture, and the shearing might plausibly have occurred since the subrounding of the boulders was produced. The brecciated rim rock also shows shearing and slickensiding.

In each structure, mining has encountered a transverse horse of unmineralized sandstone and cherty clay so pronounced that Grawe, who describes the two pits as twins, notes that each deposit itself is twinned. In both, the ore dipped anticlinally away from these buried ridges. Although in general it dipped synclinally into each deposit, in No. 2 it dipped northward at the north end and southward at the south end, becoming in each place "interlayered and mixed with sandstone, chert, and clay, apparently feathering out toward the walls of the sink structure" (Grawe 1945).

The ore bodies had many other irregularities of form, structure, and relationship to sandstone. Most significant were what appear to have been large-scale intertonguing of ore and sandstone near margins of the deposits, recognized by Crane. Although the hematite has shown no bedding in itself, these intertonguings of ore are tabular and lie between, or are separated by, sandstone strata.

Crane also described stringers and lenses of chert, clay, and sandstone *in* the hematite in No. 1, and Grawe described interbedded chert and sandstone *in* the pyrites of No. 2. Crane believed that those he saw were relics of "what was formerly a cherty limestone."

Exploratory drilling in the bottom of No. 2 has penetrated 300 feet deeper without finding rock *in situ*. Drusy chert, a trustworthy lithological marker for the Potosi formation, was encountered associated with pyrite in this hole, justifying Grawe's conviction that the bottom of the structure is as deep as the Potosi dolomite. Its present depth, therefore, is in excess of 400 feet, deeper even than the known depth of the Rueppele structure and far below the bottoms of any stream valleys ever trenched into this part of the Ozark plateau. No. 2 contains beds of buff "cotton rock" with thin shale partings, perhaps subsided Jefferson City material. It contains shale and sandstone suspected of being Pennsylvanian material; if it is, the vertical range of the No. 2 structure may well have been of the order of 500 to 600 feet. Surely such a structure can be differentiated from modern sinks that have become plugged and filled with alluvium (Grawe, 1945, p. 51).

The cavern-collapse origin of these structures has been highly favored. Nason favored deposition of the ore after the cave roof had failed, "percolating water charged with iron . . . gradually replacing the soluble (broken) rock with iron". Crane apparently, and Grawe, definitely, believed that the iron sulfide was deposited before collapse occurred. Crane was convinced that some of it was a replacement of "the more calcareous of the associated rocks". All three

recognized that the cherty clay selvage of the pits was insoluble residue from limestone or dolomite, and to that extent recognized the process advocated by Marbut (1907) and believed by the writer to have made most, if not all, of each of the Cherry Valley sink cavities.

Simmons Mountain Hematite Mine

The hematite deposit exploited by the Simmons Mountain mine, just outside the corporate limits of Salem, Dent county, (W½ sec. 24, T. 34 N., R. 6 W. Fig. 1, Sm), constituted the core of a semi-isolated knob on a divide. The outcrop of ore was centrally situated on the knob summit, about 40 feet higher than adjacent parts of the ridge and about 100 feet above valley bottoms on either side. The ridge is a relic of the Ozark peneplain and the "mountain" knob has survived later erosional attack chiefly because of the high resistance offered by its quartzitic sandstone, which wraps around the core of hematite.

This enclosing sandstone dips centripetally at steep angles. It is rim rock without any bounding wall rock *in situ* for the upper 40 feet. Mining went to the bottom of the deposit, 200 feet below the summit and 100 feet below the adjacent valley floors. Schmidt (1872) correctly interpreted the exploratory shafts as indicating that the enclosing quartzitic sandstone rim rock converged with depth, and that the hematite body had an inverted conical shape. White clay and chert were encountered between the dipping sandstone "walls" and the ore body.

Nason (1892), just before final exhaustion of the ore, reported that much of the sandstone adjacent to the ore contained chert nodules, rare elsewhere in the local Roubidoux sandstone. He speculated that the chert was a product of changes during the making of the structure, its silica being derived in colloidal form from the sandstone.

This does not explain the chert in the white clay, however, nor the clay itself. Decomposed clay and chert in other hematite pits, Nason interpreted as derived from alteration of adjacent dolomite walls. Simmons ore body, however, had no such walls, for it reached down barely to the top of the Gasconade dolomite. This writer visualizes a former extension of the structure up into once overlying Jefferson City dolomite, from which much of the clay and chert came.

The sandstone is folded and sheared near the old tramway cut (Pl. 4, fig. 1.), and elsewhere is brecciated with but slight relative shifting of fragments. The interstices are filled with quartz and hematite which both Nason and the writer believe to be vein deposits. Such structures and such deposits testify to development at considerable depth. Surface sinks could never provide the proper environment. Cave wall rock rarely shows shearing from load, and cavern solution seems oddly associated with vein deposits of quartz and hematite in fallen roof rock. The writer believes that the Simmons Mountain sink structure was made long before the Ozark erosion cycle had lowered the region to the level of the highest surviving hill tops, and that it has never been an open cavity.

The sink structure may extend down below the bottom of the hematite deposit, for at such depths there is dolomite in sufficient thickness to account for the subsidence. It is possible that pyrites or more hematite lies below the sandstone at which the mining stopped. Operators of Cherry Valley No. 2 and of Moselle No. 10 thought for a time that they had reached the bottom of their ore deposits but later discovered that they had been dealing with intercalated sandstone bodies.

How high, stratigraphically, did the original structure extend? Nason reported Mississippian crinoid stems and their casts in the Cherry Valley ore, the original material completely replaced by hematite. The nearest Mississippian formations are now 40 miles to the northeast, down the steep eastern flank of the Ozark so-called dome. Less than 35 miles of erosional stripping would be required to carry the westward-retreating edge of a Mississippian cover from Simmons Mountain to the nearest outliers of the Springfield (Mississippian) plateau. Also, Cherry Valley may contain Pennsylvanian sandstone and shale, the nearest surviving body of which is at Cuba, about 10 miles northwest. Only 20 miles of northward retreat of the Pennsylvanian outcrop from Simmons Mountain down the north slope of the dome would be required to bring about this same relation. Because Simmons and Cherry Valley mines are only 20 miles apart, we may justifiably believe that portions of both Mississippian and

Pennsylvanian systems once overlay the site of Simmons Mountain and were involved in the original structure. But a widespread sub-Mississippian unconformity probably debars us from adding any post-Jefferson City, pre-Mississippian formations to the load. However, there is adequate ground for conceiving of many hundreds of feet of rock above the bent, broken, and sheared Roubidoux sandstone in the upper walls of the Simmons mine pit.

Clay Pockets of the Bourbeuse-Gasconade Divide

McQueen (1943) mapped more than 800 "pits" (pocket deposits), containing flint, burley, and diaspore clay of early Pennsylvanian age in a group of six adjoining counties just south of the Missouri River. As many as 97 lie in one township. McQueen's map also shows about 280 flint clay pits in four counties across the Missouri, directly north of this larger group. About 30 plastic clay pits are shown in these four counties but only one associated diaspore and burley clay deposit. In contrast, there is no plastic clay pit in the larger group south of the river.

Flint, burley, and diaspore occur in different proportions in the large majority of the total number. Nevertheless, the map (Fig. 1) shows a gregarious grouping of flint pits in some localities, of burley and diaspore pits in other tracts, and of plastic clay pits elsewhere. The grouping apparently must have some genetic significance. McQueen believed that leaching of the more soluble sodium, potassium, calcium, and magnesium salts, and even of silica, had occurred in the pockets, the graded developmental series ranging from plastic clay through flint and burley to the end product, the high alumina diaspore clay. He noted that the northern district's pockets are all relatively small, and was inclined to see this difference in capacity of "leaching pot" as the cause for the segregation. Because no blanket-type Pennsylvanian clays of Missouri are of refractory grade, it seems very probable that the high aluminous composition is a consequence of experiences after subsidence into the filled-sink structures.

Most of the clay pits south of the Missouri River are abandoned or but little more than prospect holes. Only a representative group of well-opened ones, distributed along the divide between the Bourbeuse and Gasconade Rivers, was studied. This divide, like other uplands between Rolla and Cuba on the south and the Missouri River on the north, is capped with Pennsylvanian basal sandstone and conglomerate, the Graydon formation. Together, these sandstone-covered hill lands contain all but five of the pits mapped by McQueen which show the subsidiary grouping of dominantly flint and dominantly burley and diaspore deposits. This grouping is an unsolved problem.

The Graydon sandstone of the uplands, in proximity to the clay deposits, behaves as does the Roubidoux sandstone about the hematite and pyrites deposits farther south. The clays are contained in bowls or funnels formed by the in-dipping sandstone. True wall rock (Jefferson City formation) has been reported from very few pits.[6] Deformational structures in the Graydon duplicate those of the hematite-filled sinks and of the sink structures containing sandstone, colored shale, and dolomite masses—shearing, minor faulting, slickensiding, corrugations along the strike, thickening and thinning from squeeze of thin sandstones embedded in shale or clay.

The most comprehensive display of these deformational structures known in any one excavation is in the walls of the abandoned Terrill pit (sec. 26, T. 40 N., R. 8 W. Fig. 1, T), Maries County, where the clay was of desirable quality almost to the sandstone itself and the exposure of sandstone, therefore, is unusually good, and will so remain for a long time. At the southeast corner of the pit, a sandstone layer 6–12 inches thick in the basal part of the clay has been minutely fractured, the breaks running along the strike but uniting and dividing at low angles. Tiny veins have healed these fractures. This layer also is corrugated and has been thickened and thinned in the wrinkling. The bed dips approximately 40° into the pit. Near by, the stratification in the clay is vertical.

On the west side of the pit, thicker sandstone

[6] A drill hole on the north edge of the Hensley clay pit, near Bland, (SE. ¼ NW ¼ sec. 15, T. 41 N., R. 6 W.) showed a rubble of Jefferson City chert mingled with sand or sandstone to a depth of 165 feet, where Roubidoux dolomite in place was entered. Personal communication from John Grohskopf, Asst. State Geologist of Missouri.

strata dip up to 80° into the pit and show squeezed indentations and projections on both top and bottom sides, with relief as much as 8–10 inches. One minor sandstone layer in the clay has been squeezed into typical boudins, resembling a string of sausages, ranging from 6 to 18 inches thick. It is also cut by a minor fault exhibiting a glassy, quartzitified and slickensided face with striae leading diagonally down into the pit. The opposite side of the fault has been destroyed in the excavating.

The clay in most of the pits shows some stratification, its dip conforming with that of subjacent sandstone. Detailed deformations, however, are not common, apparently because of a uniform yielding of the massive clay to stresses imposed by subsidence. Slickensided surfaces dip toward structural centers. Joints, the most common structures, usually dip steeply out of the pits and their prevailing strikes are roughly tangent to pit ground plans. One pit, on the south side of Missouri Highway 28, about a mile east of Bland, Gasconade County, showed on its flat bottom a series of imperfect and discontinuous vertical curved joints traces, resembling the pattern of an equatorial section of an onion. Quarrying in the center had been guided by one of these curved joints and the deepest hole in the floor had a nearly perfect 5-foot circular wall around half of its circumference. Neither McQueen nor the writer saw slickens on any joint faces. Jointing appears to have been tensional.

Slickensides, where present, definitely record downward crowding of the clay; the joints may be manifestations of a weakened basement because of further solutional removal of dolomite below. This could be a condition precedent to more settling.

A Harbison-Walker clay pit (sec. 25, T. 40 N., R. 8 W. Fig. 1, L.) about 2 miles west of Lanes Prairie had, in 1946, a nearly vertical clay wall left by the dragline. It showed an almost complete cross section of an asymmetrical syncline, (Pl. 1, fig. 2). The pit was approximately 100 feet deep and 150 feet across and virtually every thick-bedded unit of the clay could be traced down into, and across, and up out of this fold. The thickening and thinning involved considerable length in any affected stratum and was not the rather sharp deformation the intercalated thinner sandstone layers show in such pits. Jointing was not conspicuous; faulting and brecciation appeared to be completely lacking. The writer believes that the clay in this pit had been deformed by very slow movement, not by any one collapse nor by any series of smaller collapses.

Another Harbison-Walker pit (NW ¼ sec. 29, T. 41 N., R. 7 W., Fig. 1, B) 1½ miles south of Belle, Maries County, was 90 feet deep at the time of examination and was reported to have another 90 feet of clay below the bottom. In the upper walls were separate masses of internally deformed sandstone, all dipping centripetally, some as much as 60°–70°. A trench cut across the upper east wall exposed perhaps 75 stratigraphic feet of interbedded sandstone and colored shale, all dipping into the structure and either cut off by, or going beneath, the marketable central clay.

This structure's ground plan departs markedly from the conventional bowl or funnel shape. It is an elongated syncline, its axis striking a little north of east. A prospect pit 1500 feet farther east, across a small valley, may be in the same structure. If so, it is the most elongated clay pocket yet reported and comes nearest to what the writer insists would be the outline of many sinks if cave collapse had made the structures.

Many of the clay deposits of the Bourbeuse-Gasconade divide carry a few feet of stratified gravel, composed mostly of chert but with some sandstone fragments. Thicknesses range up to 12 feet at the Peizuch pit (NW ¼ sec. 11, T. 42 N., R. 5 W. Fig. 1, P), 4½ miles northeast of Owensville. The largest pieces are sandstone cobbles and boulders with diameters as much as 2 and even 4 feet. There is very little interbedded sand. The unsagged gravel cover truncates the tilted clay strata beneath. The making of these clay-filled structures therefore was completed before this upland flat country was a lowland of stream deposition.

The six counties containing the more than 800 clay pits (McQueen) also have a known total of 94 caves, all past their phreatic stages of growth and all suffering more or less from collapse. Yet no intersection of cave and filled sink is known. Cave collapse certainly has not made or deepened any known sink structure in

the region since the gravels were deposited on the peneplain[7]. Uplift of the peneplaned Ozark dome probably began in its central area, farther south, and the ancestral Gasconade became rejuvenated first in its headwaters. This northern gravel-covered part of the peneplain thus became a site of deposition because of the lack of adequate gradient here for carrying away the load brought by quickened headwater tributaries.

Blossom Rocks

Blossom rocks are outcropping masses of sandstone, ranging from boulder size up to several acres in area, their bases set into cavities in subjacent dolomite but their tops projecting above the surface. Stratification, if present, is disturbed, jointing is commonly close-set and "without system", and there may be numerous other cracks, now "silicified" (Lee). Slickensides in the sandstone are reported. Adequate exposures show a whitish clay between the sandstone mass and the partially enclosing dolomite. Blossom rocks are scattered over the area of the filled sinks in much greater numbers than the map (Fig. 1) shows and clearly are related to them. Indeed, the Otterville sink structure, without the highway exposures, would be classified as a low blossom rock.

Marbut (1907) and Lee (1913) have described these features. They recognized that groundwater solution was involved in emplacement of the sandstone masses, but they differed markedly in the details of their respective interpretations. The name was proposed by Lee. Neither one attempted a concise definition.

Lee described one of these features as exhibiting a gentle anticlinal and synclinal structure, with an accompanying outward dip of the enclosing dolomite. This he thought was due to folding subsequent to emplacement. Another had centripetal dips averaging 25° "probably due to secondary solution beneath the mass and settling." Marbut, to whom he refers, had already proposed this idea as the whole cause. Lee, however, preferred to think that "these deposits represent the filling of subterranean caverns either during their formation or at some subsequent period". He found a vertical range of 250 feet and a maximum exposed thickness of 55 feet among the blossom rocks of the Rolla quadrangle.

Two blossom rocks outside the areas treated by these investigators were studied by the writer. One is Standing Rock, at the east end of Standing Rock Ridge, in Camden County (SE ¼ NE ¼ sec. 20, T. 39 N., R. 17 W.). Its cliffs and ledges rise 20 feet in the clear above a talus slope of fallen blocks another 20 feet high. Clean-cut vertical joints, belonging to two sets intersecting approximately at right angles, have guided the weathering attack and produced a striking assemblage of pinnacles and blades. The gray, uniform sandstone is otherwise firmly indurated, the joint-determined, sharp edges of blocks being retained even in the talus material.

On the southern side of Standing Rock, the sandstone contains a nearly vertical zone of scattered, unsorted, unworn chert fragments ranging through perhaps 3 feet of thickness back in the cliff. This is the only stratification shown, and the only chert in the entire outcrop.

Fowke (1922), an archaeologist, adopted the idea that Lee advocated for blossom rocks and called this Standing Rock a "fossil cave". The surface is "an exact cast of the interior of the cave which it filled, and nodules of chert remaining when the limestone was dissolved, are still embedded in its surface".

Another example of blossom rocks, unmentioned in geological literature, is just west of the bridge carrying State Highway 19 across Standing Rock Creek, Dent County (N ½ sec. 34, T. 33 N., R. 5 W.). It is a steep-sided, narrow, irregular, blade-like outcrop of clean gray sandstone, its pinnacles rising about 20 feet above the stream at its base. Although there are a few chert fragments in it, no positive identification of bedding can be made. The rock is cut by a multitude of irregular, criss-crossing planes which make little ridges and blades on the weathered surface. There are suggestions of weathered slickensides on some of these. Lying detached near the summit, in 1946, was a large fragment of the sandstone, with excellent slickensides with parallel striae on one face.

[7] These "Lafayette" gravels are too thick and too widespread and some of them too coarse to be records of base-level streams. "Gravel is to be expected in the alluvium associated with a peneplain as in any other alluvium on a suitable grade, but within that area that is typical peneplain and not something else, nothing is scarcer or less expectable than gravel (Fenneman, 1936).

Dolomite strata crop out about 100 feet upstream, with a dip of 10°–12° away from the Rock. Another outcrop, 200 feet distant upstream, shows only flat-lying Gasconade dolomite.

The Rock certainly is not in place, certainly has been deformed. Although no faulting is yet known in the region, the local dip of the dolomite suggests it. This Standing Rock may not be a good example of true blossom rocks. But, if it is, a minimum of subsidence is necessary if it is Roubidoux sandstone, considerably more if St. Peter or Graydon sandstone. Considering the displays of subsided sandstone masses in so many filled sinks of the northern Ozarks, these blossom rocks might be the very bottoms of such former structures, all else having been removed by erosion. Lee notes that one blossom rock "lies below and not far distant from a fire clay pit." But the lack of good showings of clay-with-cherts beneath blossom rocks deprives that argument of its strongest supporting evidence. The writer believes, however, like Marbut, that they are subsided masses, let down gradually and deformed during the settling.

Conclusions

The twenty filled-sink structures described and two more to be described under the "Circles" and "Filled Caves" categories to which they have been erroneously ascribed are interpreted as products of slow, compressional subsidence, under a former load, into enlarging solutional cavities in subjacent calcareous formations, no cavity ever having been an open space in the rock.

The extraordinarily large vertical and small horizontal dimensions, although debarring the widely favored collapsed cavern hypothesis, have defied explanation by the preferred interpretation.

Circles

Definitions and Interpretations, from the Literature

Circle deposits have not been clearly differentiated by all writers from filled-sink deposits. The writer follows Mather's (1946) proposal that the term circle deposit be applied only to solution cavities (1) filled with "broken rock which has accumulated by the spalling and caving of wall and roof rock"; (2) circular in ground plan and cone- or bell-shaped in cross section; and (3) without rim rock. Thus a circle is a collapse-formed cave, filled with its own country rock debris. Mather limited the term sink (filled sink) deposit to cavities where solutional removal of fallen wall and roof rock debris in a former circle deposit had caused the unsupported roof to cave, forming a funnel or inverted cone in cross section, and engulfing overlying strata to give rise to rim rock. "It is conceivable that these two types of deposits are transitional one into the other". (Mather 1946, p. 49)

The description and explanation for circles of the Joplin region by Smith and Siebenthal (1907) fails to differentiate them from filled sinks. Some circles had rim rock and debris fills from superincumbent strata and from surface sinkhole waste. These authors also included some annular ore bodies which surround cores of solid rock[8]. They believed that collapse or perforation of cavern roofs was a pre-requisite for all these fillings, the solid rock core of the annular ore bodies recording the intersection, at an adequate angle, of two sets of two parallel cave chambers.

The ore bodies of southwestern Missouri known as runs and circles (Smith and Siebenthal, 1907) are limited to "disturbed strata which have been subject to brecciation, slickensiding and moderate displacement as a result of minor faulting or of dislocation due to underground solution." Both are relatively narrow, horizontally elongated bodies which grade into each other as straight linearity passes into curved ground plans. The mine maps, in the Joplin folio, of compound and irregular runs show a complicated interlacing of workings that suggests some cave maps. Repeated use of the terms "underground solution", "underground drainage" and "underground channels", the comparison with Mammoth Cave, Kentucky, and the insistence on a pre-Cherokee karst in the region indicate the preference of the authors. They have, indeed, the only really elongated sinks and the only ones possessing a system of transverse and lateral members known in Missouri.

But the large contorted masses of Pennsyl-

[8] Distinction must be made between the circles here described and such annular ore deposits, also called circles but not associated with a bell-shaped, breccia-filled cavity.

vanian shale 150 to 200 feet below its proper stratigraphic level, the depressed, elongated patches of shale on the surface over the runs and circles in Mississippian rock, the prevalence of slickensiding, the in-dip of adjacent limestone, and the great brecciation of heavy chert beds that have sagged down but are still traceable across the structures are all features of filled sinks, foreign to the character of circles as here defined and to known collapses in caves. "Underground solution" is the correct explanation but the idea should be sharpened by specifying that it occurred under a load of superincumbent Pennsylvanian strata adequate to close all cavities from above before they grew to cave sizes.

Bain (1901) considered that the circle deposits of the Central mining district were "probably in many cases sink holes in which the ores have accumulated mechanically and residually", but that faulting might have determined some. The larger circles of the Southwest mining district of Missouri were "so closely related to certain definite fault planes that it is impossible to refer them to the category of sink holes" (or to any other kind of ground water work). Siebenthal (1905) convinced him (Bain, 1905, p. 172) that he had overestimated the number of faults and the amount of faulting. Bain's circles of the Southwest mining district were "usually, if not always, associated with more or less shale presumably belonging to the Coal Measures", and much of the faulting he saw must have been deformation produced by filled-sink subsidences.

Winslow (1894, p. 465–467) believed that, in southwestern Missouri, pre-Pennsylvanian sink holes were initiated by interstratal solution of limestone between chert beds, producing "a settling of the ground and a fracturing of the chert beds". In the depressions thus formed, Pennsylvanian shale and coal pockets were deposited.

"Later subterranean solution would result in further settling under such pockets, causing the beds to assume steep dips, or even brecciating them. . . ." "To be included under the head of breccias are, further, the fillings of those peculiar deposits of the Central district, known as circles." "They are essentially deposits filling wide circular cavities or chimneys, 50 to 100 feet in diameter, which generally widen out laterally with depth, down to certain limits, so that the space occupied within the surrounding walls has the shape of an inverted (sic) cone. The most natural explanation of these deposits is that they are fillings of caves which had vertical openings leading to the surface."

Winslow did not clearly distinguish circles (containing only wall and roof rock debris) from filled sinks (with downward-intruded and deformed younger material). Nor did Schmidt (1874).[9] Meek (1855, p. 117–119), apparently the first geologist to use the term, cites what is a true circle in Mather's (and the writer's) sense. Although Meek curiously missed the obvious origin of the fill, ascribing it to an upward thrust, he clearly found no subsided debris in his type.

Mather's definition of filled sink includes the cave-collapse genesis which the writer denies. Sinks are not descended from earlier circles. Indeed, it seems probable that circle-making came after filled sink-making in the region's history.

Circles and Filled Sinks of Morgan County

In Mather's report (1946) on the mines, diggings, and prospect holes of Morgan County, 145 are classified as barite properties, 15 as lead and zinc, 16 as coal and 22 as fire clay deposits. Accepting his distinctions (sometimes inconsistent) between circles and sinks, there are 8 probable circle deposits, containing barite, galena, and sphalerite, 25 ore deposits probably in solution channels, cavities, and caves, and 9 probably in sinks. The remainder were judged to be in fissures, fractures, and brecciated zones, and in surface residuum.

Almost all the circle and solution cavity deposits were specified as also containing red clay while only two of the probable sink deposits had it. None of the circles contained Pennsylvanian or Mississippian material, all the sink

[9] Schmidt, reporting on the Oronogo "circular diggings" of the Joplin district, recorded at least 25 shallow shafts aligned about the periphery of a flat basin 400 to 500 feet in diameter. "The fact, (revealed by the shafts), that all the layers, irregular as they are, . . . invariably . . . (dip) toward the center of the circle, decidedly supports" the view that upper strata had subsided into a large cavity in the underlying limestone. Furthermore, a central shaft penetrating 104 feet below the level of the surrounding Mississippian limestone, showed "a confused mixture of broken Coal Measures rocks" to the bottom.

fillings did.[10] All the coal and clay deposits were diagnosed as occupying sinks, none was reported to have any associated red clay.

On the basis of 198 workings in one county, the circles are characterized by the presence of red clay and the absence of debris from once-overlying formations, and sinks by subsided younger rock but absence of red clay. This generalization obtains in virtually all sinks and circles known to the writer or sufficiently described in the literature. Red clay is a widely occurring cave deposit in humid regions where weathering makes a red residual soil on a calcareous terrane.

Oronogo Lead and Zinc Mine

A well-known lead and zinc deposit in southwestern Missouri, repeatedly referred to as a circle, is the Oronogo mine (sec. 36, T. 29 N., R. 33 W.). By almost all the criteria adduced in this study, Oronogo is a filled sink, not a circle. It is a huge structure, 800 feet by 650 feet in diameter and had been excavated, by 1946, to a depth of 230 feet. The original detrital filling has been largely removed to this depth and the original funnel shape (Guy Waring, supt. of the mine, personal communication) has been altered to one more like a cylinder as ore in the deeper wall rock has been mined.

At the north end of the pit, a breccia of limestone and chert fragments in black contorted shale comes sharply into nearly vertical contact with the Mississippian limestone wall rock. There is no rim rock here, for there is no sandstone, and limestone or dolomite rarely make rim rock. The limestone is marked repeatedly by steeply inclined groups of slickolites, not bedding plane stylolites, for as much as 15 feet back from the contact. In all cases, the slice nearer the pit has gone down. At the contact, some chert pebbles of the fill, impressed into the limestone, have been dragged down the face, leaving gouges and striae behind them. Some limestone boulders in the breccia carry variously oriented groups of slickolites on their surfaces. Some have solutionally rounded and even solution-pockety surfaces.

Debris being shot down from about the 100-foot level in 1946 was fill material with coal and carbonaceous clay in it. The dark smutty color in places in this south wall of the pit indicated Pennsylvanian material 200 feet below the surface.

On the south side, where underground workings penetrate back into wall rock from the bottom of the pit for some thousands of feet, a linear cave about 10 feet wide and high has been encountered. It was full of water when first broken into and is completely lined with dogtooth spar. Although in the belt of mineralized "sheet-ground" extending from Duenweg north past Oronogo, it is outside the collapse breccia entered by the pit. Being an open cavity without mineralization in rock mineralized by replacement, it would seem to be younger and therefore not a remnant of any hypothetical cave preceding the collapse.

The Oronogo structure has all the ear marks, except sandstone rim rock, of a filled sink, and none commonly ascribed to circles. The Grand Falls chert member exposed in the pit walls is cut repeatedly by peripherally striking, steeply in-dipping shearings, whereas the walls of circles are cut by prevailingly out-dipping and originally open fractures. There was a greater concentration of ore in an annular body about the periphery of the deposit, but this feature is repeated in sinks as well as circles and is not a criterion.

Conclusions

The outward-dipping fractures of wall rock in circles are filled with veins of sulfides, barite, and calcite. They are tensional fractures, quite unlike the sheared and slickened fractures of filled-sink walls. The upward convergence of circle walls and the fill of nothing but wall- and ceiling-derived fragmental material both indicate that circles are collapse-formed domes, comparable to many such in existing caves.

The concept of circle origin by cave collapse has to meet four objections: (1) Caves are linear whereas circles are nearly equidimensional in ground plan; (2) No circle is known to be connected with a cave; (3) The debris fill is essentially complete. Most collapse debris piles in caves fail to reach the ceiling; (4) Known circles do not have roofs.

The first and second objections are met if the original cave roof failed only locally. The collapse cavity, once initiated, migrated up into

[10] The county has no remaining Pennsylvanian overlap *in situ* and only a few square miles of Mississippian.

roof rock until a stable dome form was developed, bell-shaped or cone-shaped in cross section. The tensionally cracked wall rock is a part of this procedure. Mather's apt comparison was with the caving of large circular areas of roof rock in the lead mines of southeast Missouri. The level of the original cave presumably lies deeper than any mining has gone.

The third and fourth objections are met if erosion, since the collapse fill was made, has removed the rock in which the upper part of the cavity lay.

Ore-bearing solution channels, cavities, and caves are related to circles by the common possession of red clay. Sink fills almost universally lack red clay. If this criterion is of any genetic value, filled sinks have not descended from, and are not related to, any former open solution cavities.

Winslow (1894), in describing about 70 lead and zinc deposits of what he called the Washington-Jefferson County and Franklin County sub-districts, lying just east of the filled-sink country, found no circles but noted 24 mines and diggings in which ore-containing solutional openings of cave magnitudes and patterns were encountered, most of the ore being associated with red or tallow clay cavity fillings. Tallow clay has been a common accompaniment of these ores also in southwestern Missouri, most of the cavities containing it being reported as caves. Only one sink deposit of this district contained red clay. Winslow derived most of the clay by infiltration down from the surface residuum.

The writer has found evidences of a former complete red clay fill in a large percentage of 130 caves of Missouri, distributed among more than 50 counties. Red or tallow clay is a common cave deposit and is to be expected in debris-filled cavities resulting from their collapse. Its extreme rarity in filled sink structures in limestone or dolomite terranes is a valid argument against their origin from cave collapse.

Absence of tallow clay in the filled sinks of Morgan County may mean that the limestone and dolomite was still completely covered by Pennsylvanian shale and sandstone when subsidence occurred. It must mean this to proponents of the cave-collapse theory. Because collapse openings are not necessary for filtration of clay into caves, and because the existing open caves of the region contain no Pennsylvanian deposits, these caves are post-Pennsylvanian in age. They have been made, filled, and partially re-excavated since the region was stripped down to the Ordovician dolomites. Thus the circles, which clearly are collapsed caves, must be much younger than the sinks.

The writer's present interpretation of clay in Missouri solution cavities may be generalized as follows. The clay of caves, solution channels, and cavities and of the circles is surface residuum that has migrated down. The clay of the filled sinks is either Pennsylvanian sediment that has settled bodily or is a residuum from sub-surface solution of the local calcareous bedrock below the level of oxidizing ground water. Filled-sink clay that is red, brown, maroon, or purple was originally a colored sediment or has become colored during later oxidation in the sink.

Circles, as here defined, are small compared with most filled sinks, approximating the diameters of the larger chambers of Missouri caves. Among the caves of the writer's study, scarcely one has a chamber large enough to account for the area of the average filled sink.

Filled Caves

Definition

A limestone cave is a roofed solution cavity large enough to admit the human body. Most caves of the Ozark region ceased growing when a fill of red clay derived from surface residuum obliterated them as open cavities. The work of ground water in them today is limited largely to removal of that fill. The red clay deposit could never have been made under present regional conditions and therefore antedates the present topography and its influence on ground-water flow. The caves, in turn, must antedate this fill.

Caves developed during the long pre-Pennsylvanian erosion, filled with Pennsylvanian sediments and never suffering collapse, are reported from Missouri but have yet to be found in the region of the filled sinks. Of the right age and in the right situations to receive Pennsylvanian material like that in many sink structures, they are a part of the filled sink problem. If the sink structures are lineal descendants of pre-Pennsylvanian caves, there

should be some intermediate examples. The circle deposits come to mind: Are they intermediate stages in the evolution of filled (or unfilled) caves to filled sinks?

FIGURE 20.—MAP OF VALLE'S MINE, JEFFERSON COUNTY

After Winslow

Washington and Jefferson County sub-district

Lead and zinc mining in four counties just east of the filled-sink region found much ore in filled caves whose proportions, magnitudes, and patterns duplicate many of the open caves of the Ozarks. Some were only partially filled but none is reported to have any surface opening or any stream of water on the floor. Many were discovered in mines so deep that they must have been below the water table. (Winslow, 1894; None of these mines can now be entered.) The sulfides were found in a red tallow clay or adhering to the wall rock. Patterns like that shown in the Valle mine (secs. 7 and 8, T. 38 N., R. 5 E.) map (Fig. 20) indicate control by both bedding planes and joints and are closely comparable to a number of air-filled and readily enterable Ozark caves.

There are also close resemblances between these caves and the lead- and zinc-bearing caves in and near Dubuque, Iowa (Bretz, 1938), involving pattern, occluded condition, clay fill, and sequence of ore and clay deposition. In neither region are the caves large enough to have suffered roof collapse on a scale adequate to explain filled-sink structures.

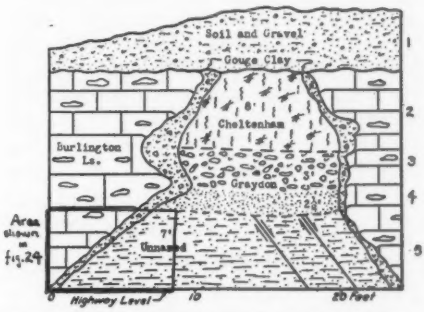


FIGURE 21.—"FILLED CAVE", COOPER COUNTY

From McQueen

These ore-bearing filled caves probably belong to the same generation as those now occupied by air above a stream flowing on the remainder of a clay fill. They are all dated back to the maturity of the Ozark cycle of erosion. The red clay is ascribed to the slackwater condition later imposed on them beneath the Ozark peneplain. The filled caves of the two mining sub-districts may belong to an earlier generation; they must be older than the latest episode of sulfide deposition. They surely have no genetic relation to filled sink structures, and no circles were reported among them.

"Filled Caves" in Cooper County

The western bluff of Lamine River valley, where crossed by U. S. Highway 40, has been deeply trenched to secure a highway gradient. Exposed in the walls of this cut are several solution cavities (SW ¼ SW ¼ sec. 12, T. 48 N., R. 19 W) in the Burlington limestone, described by McQueen (1943, p. 30–33) as "caverns, chimneys, caves or sink holes", all filled with clastic material which McQueen identifies as Pennsylvanian Cheltenham clay, Graydon sandstone, and an "unnamed formation" (Fig. 21) Extensive sliding in the fill and overburden have now obscured all but the eastern (left) end of the exposed fill, entirely

in the "unnamed" formation. Because it lies offside, however, the structure in this "toe" should be decipherable for some time.

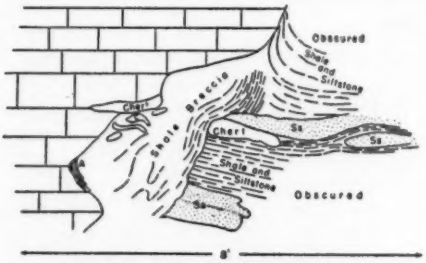
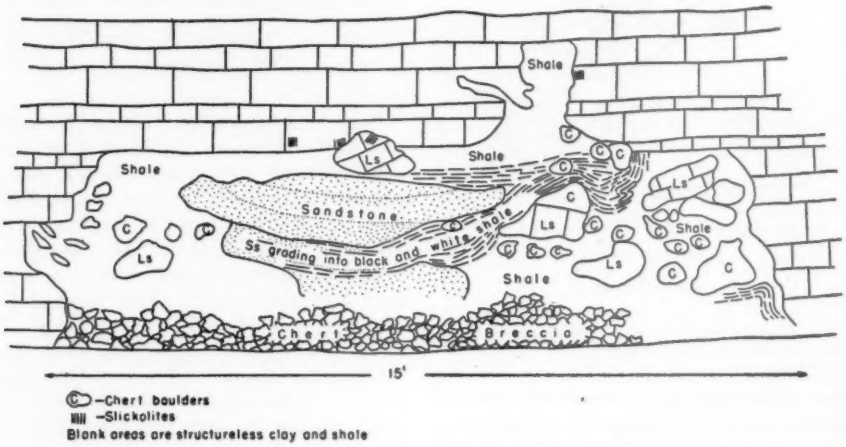


FIGURE 22.—TOE OF "FILLED CAVE" SHOWN IN FIGURE 21

(Bretz, 1940) possess this overhang, and also commonly show another feature, equally rare in Missouri, which this filled cavity possesses, horizontal moldings and grooves on the edges of the wall rock strata with a peculiar fitting of shale laminae into the grooves (Fig. 22, A).

A few hundred feet farther west, another filled solution cavity (Fig. 23), completely roofed in the section and with an overhanging back wall, looks at first glance even more like a filled cave. Central in the section is a body of Pennsylvanian sandstone, apparently nearly horizontal, associated with somewhat deformed shale. This sandstone, however, is strongly warped at right angles to the section face, dipping back into the wall from a few to as



FIGURES 23.—WESTERN "FILLED CAVE" IN CUT OF U. S. HIGHWAY 40, COOPER COUNTY

Convincing evidence was displayed in 1948 that the Pennsylvanian material is an intrusion, not a cave fill (Fig. 22). If a cave once existed here and became filled during Pennsylvanian time, as McQueen visualizes, there has been subsequent deepening, and probably widening also, so that the fill materials have become deformed by subsidence in typical filled-sink fashion (Kansas Geological Society, 1941, Figs. 7, 8, p. 22).

Two of the solution cavities at this place, unlike all others seen during this study and most described in Missouri literature, have overhanging walls like those of circles. Cavities of filled-sink origin in northeastern Illinois much as 45°. The associated shale, traced westward, becomes vertical and terminates thus against the "cave" roof. It also has a tight little S fold in it. The localized structures in the shale, as far as shown, are traceable to the effect of embedded blocks of chert, limestone, and sandstone which moved differentially during the subsidence.

The chert breccia has a sandy matrix. No limestone fragments were found in it. It could pass for an insoluble accumulation on a cave floor, though not from the limestone that has been removed in making the visible cavity.

The feature of this cavity fill which is wholly impossible in any cave is the limestone boulder

on top of the tilted sandstone, *impressed into* the wall and roof rock for nearly half of its total surface. It bore excellent slickolites (Numerous conventional, Burlington type, bedding plane stylolites are close at hand for comparison) and several solution pockets, 1–2 inches wide and deep. These pockets were filled with shale and each filling was a series of concentric shells fitting the pocket. Similar pockets and contents exist in the filled cavities of northeastern Illinois, some of which, on under sides of projecting moldings, must record upward-directed, pressure-determined local solution. Slickolites to show this direction of movement accompanied these Illinoisan pockets. There is no consistent orientation in the boulder in this section. Although the block lay in a shallow pocket in the wall rock, there was 1–2 inches of carbonaceous clay between, laminated to conform to irregularities in the limestone. In other words, the boulder had forced Pennsylvanian clay ahead of it into the wall and roof rock. Unfortunately, most of this exhibit had to be destroyed in the course of the examination.

This western cavity of the highway cut therefore is another "toe" of a filled sink, and its contents have been forced into it as it grew. The major part of the structure lay where the highway now is. Neither of these fills belongs to the filled cave category.

There is no red clay in either filling. A third cavity, between the two and smaller than either, is filled entirely and only with a hard red clay. It belongs to the existing generation of Missouri caves, its fill being derived from the oxidized clay fraction of the Ozark peneplain's soil.

Filled Cave in Cole County

A highway cut along U. S. 54, on the divide between Moreau and Missouri rivers, shows a roofed and filled cavity in Jefferson City dolomite. The fill consists of black shale, containing thin slabs of chert or weathered limestone arranged in parallelism with the sagged strata of the shale and its interbedded clay and chert debris. The 6 feet of roof rock, however, is unsagged. This feature may be a filled cave, or it may be another "toe" of a filled sink. If the latter, the detrital fill was pushed diagonally into it with surprisingly little deformation.

Filled Cave in Montgomery County

A quarry along Highway 29, about 4 miles south of Montgomery City, has breached the wall of a large cavity in Calloway, Chouteau, and lower Burlington limestone. It is filled with chert fragments, Burlington boulders, and Pennsylvanian green-gray clay shale. The fill has a rude stratification, three very cherty members being separated by two shaly members. No deformation is shown, either in the fill or the wall rock (Kansas Geological Society, 1941, Fig. 23). An unsagged roof of Burlington limestone, about 20 feet thick, carries 10–15 feet of surface chert waste resembling that of the chert members in the fill. The Burlington roof and wall rock is only sparingly cherty and all this overlying debris must have been derived from higher horizons since eroded away. That in the cavity, however, must date back to a pre-Pennsylvanian land surface.

About 15 feet of this chert is in the basal part of the fill as now shown. The remaining 15 feet is mostly clay shale but contains the other two stratiform cherty bodies, one of which does not reach completely across the width of the fill.

The shale has an indistinct lamination which bends down under and also up over isolated chert fragments. They must have been dropped to position. The materials of the three cherty members record concentration elsewhere and transportation to the cavity. Modern cave floor concentrates of such coarse angular chert waste are traceable to near-by source rock, either in wall and ceiling or derived from surface weathering and entering through a sink hole.

Some large blocks of Burlington have come down at least 20 feet to present positions in the fill. Their parent ledge shows, in the section, well up in the remaining roof rock. Apparently they fell during the early history of the filling. Nothing suggests that they or their matrix constitute a downward intrusion that kept pace with the cavity deepening.

This filled cavity is accepted as a true filled cave, at least 30 feet high and 75 feet wide, which never has had any subsequent enlarge-

ment and consequent subsidence of its fill. The lack of red clay in the fill indicates that there was no peneplained land surface above the cave when the Pennsylvanian submergence occurred. The accumulation of chert cobbles indicates sink hole collection from a higher level and adequate slopes on which they travelled to reach the cave floor.

The Montgomery County filled cave, therefore, belongs to a different category than that of the filled sinks or of the circles.

Summary

The three types of filled solution cavities in calcareous rock of the Ozark region of Missouri are filled-sink structures, circles, and filled caves, each group possessing its own identifying characteristics born of its method of origin. Individual variations and sub-groups do not invalidate this classification.

The following characteristics belong exclusively to the filled-sink structures.

1. Strata of the closely adjacent country rock dip centripetally toward and into the cavity.
2. Debris from these in-dipping wall strata has been recognized, deep in the fill, as discontinuous units from wall to wall.
3. Where the calcareous country rock is capped with sandstone, the in-dip has produced low hogback ridges, the rim rock, striking peripherally about the fill.
4. Steeply inclined in-dipping sandstone strata descend across the edges of subjacent dolomite or limestone strata.
5. A selvage or gouge of residual clay-with-cherts separates the fill from the wall. Where rim rock descends into the fill, this selvage lies between it and the wall rock.
6. Slickolites in calcareous rock and slickensides in sandstone occur both at contact of fill and wall, and in rotated masses in the fill.
7. Sandstone rim rock is brecciated and sheared.
8. The fill material has bowl-shaped synclinal structures, in which are
   (1) brecciation and faulting,
   (2) shearing and slickensiding,
   (3) corrugation and complex minor folding of layers, even drag folds,
   (4) thickening and thinning of strata, even boudinage,
   (5) stylolitic penetration of coal and chert into limestone and dolomite,
   (6) replacement of fill material with pyrites in the iron-bearing sinks,
   (7) quartz veins and geodes and siliceous cementation of breccias.

Most of these characteristics are clearly the cumulative result of slow compressional stresses and all indicate origin at depth. Almost no tensional stresses are indicated in any filled sink, either in wall rock or in contents of the fill. Compaction falls far short of explaining the deformations. In districts where both sinks and caves abound, there are no known connections. Almost no sinks show the elongation that subterranean drainage ways must possess. No caves and no circles show the in-bending of wall strata or the selvage residual clay-with-cherts which characterize the sinks.

For these reasons, the deformation and subsidence of fill material is held to have closely accompanied the solutional removal of the underlying calcareous rock, no open cavities ever existing beneath the fills of these structures. The pressure necessary to produce the structures was provided by once-overlying formations, long since stripped off in the peneplanation of the Ozark so-called dome.

Circles are characterized exclusively by a breccia fill of debris from wall and roof rock. In common with many filled caves, most circles also contain red tallow clay which the filled sinks lack, except close to the present surface. Circles have no selvage or gouge of residual material and no deformed wall rock. They yield no evidence of mass subsidence from higher stratigraphic levels and none of compressional deformation in the fill. Instead of being funnel- or bowl-shaped, they are cone- or bell-shaped in cross-section. Tensional cracks dip radially out of circles into wall rock.

For these reasons, the circles are judged to be collapse-formed domes which have migrated up into the roof rock of solutionally made caves.

Filled caves known in Missouri are of two ages and contain two types of fill. A very few contain undeformed Pennsylvanian sediments. Most of them contain only a red or tallow clay fill, with or without sulfide ores and barite.

Their plans commonly indicate joint and bedding plane control of the circulating ground water which made them. They possess unfailed roofs. They are so obviously solution caves that there never have been other interpretations of their origin.

The most convincing evidences that the filled-sink cavities were dissolved in the phreatic zone are: (1) the amount of vertical subsidence, amounting to a few hundred feet in some cases; (2) the pyrites contents of some, below a hematite deposit which all agree is but the oxidized zone of the sulfide; and (3) the penetration of sink cavities well below the bedrock bottoms of adjacent valleys. Only by the gratuitous assumption of marked aridity during their development can they be considered vadose in origin, and the sulfides must then be introduced after the suppositious low water table had risen again to valley bottom levels of their time.

Filled Sink Problems Not Treated in This Paper

An outstanding problem is the areal localization, within a few acres at the most, of the pronounced solutional attack and the relatively great downward penetration within that area. Grawe (1945) thought that initial sags had localized the hematite-pyrites structures. McQueen (1943) thought that there was joint control in localizing the clay-filled sinks. The solution cavities of northeastern Illinois (Bretz, 1940), in Silurian limestone and with fills of deformed Pennsylvanian sediments, are strikingly joint-controlled but they also are much elongated along one set of joints. Intersecting joints would seem to be the logical combination for the equidimensional Missouri cavities but no field evidence has been reported, or found during this study, to support this idea.

The limitation of almost all the structures to the northern and western slopes of the Ozark so-called dome is another problem. That these are the gentler slopes appears to be no reason. More light on this question may come from a detailed study of similar structures in southeastern Missouri, in northwestern Arkansas (Purdue and Miser, 1916), and in the Kansas and Oklahoma portions of the Tri-State mining region.

A problem which cannot be ignored but which has had only scant attention in the literature is the segregation of coal- and clay-filled sinks north of the hematite- and pyrites-filled structures and farther down the slope of the Ozark dome. The two fields overlap a little (Fig. 1) and Cherry Valley lies in the overlap. Fifteen miles northeast of these mines is a coal- and clay-filled sink (sec. 11, T. 39 N., R. 2 W.) whose coal is reported to be 40 feet thick. Thirteen miles southwest of the mines (sec. 26, T. 36 N., R. 5 W.) is another such filled sink which has been explored by two shafts, excavated in vertical clay shale, one 40 feet deep, the other 80 feet. The coal bed was 8 to 10 feet thick. " . . . it bends on itself at an angle of 45 degrees" (Nason 1892). The coal was crushed and slickensided. Other instances of this overlap might be cited.

The filled sinks of Missouri are very unusual results of ground-water work. Geologists have found but few calcareous terranes which they felt recorded the proposed mechanism. If the filled sinks of the Missouri type are rare phenomena, then their causal factors have rarely coincided in time and place. For this reason, and because the only real difference between the two groups is in the fill, it seems gratuitous to assume two times of filled-sink making. McQueen's hypothesis (1943) that all sinks originally had clay above pyrite seems more meritorious, although thus far no clay fills have been shown to have pyrite beneath. The writer, however, prefers differences in the overlying rocks, chiefly the Pennsylvanian sediments, which became engulfed. The significant differences may have lain in the response of fill material to sulfide-charged ground water. Siliceous and calcareous rocks may have become replaced, while coal and the tight and high alumina clays did not.

The factor which determined what kind of fill material a developing cavity was to receive may have been the pre-Pennsylvanian relief, both local and regional. This hypothesis must assume that the sites of the hematite-and-pyrites sinks stood too high to become covered with the Cheltenham type of Cherokee shale, with its associated coal seams. Thus the two clay-and-coal sinks near the Cherry Valley hematite-and-pyrites deposits developed on a lower surface of the pre-Pennsylvanian topog-

raphy, and the mines deposits on a higher tract, above the level of Cheltenham submergence. Indeed, the Cheltenham type of clays may never have covered any of the southern part of the filled-sink area of Missouri.

The question of the extraordinary massive concentration, and the purity, of pyrites and hematite is still open. Every previous writer who has discussed the origin of the hematite-pyrite fills has reported widespread evidence that replacement was a factor. All except Nason, however, have played the theme pianissimo whereas the present writer would give it the diapason stop. When more detailed thin-section and polished-surface work is done, these iron compounds probably will be accepted as replacements. The field evidence appears to debar the theory of open cavity fillings.

Another problem deals with the question of caves contemporaneous with the sinks. Most Ozark caves are pre-peneplain in age but their red clay fills indicate a limestone or dolomite land surface above. Hence they post-date the removal of the non-calcareous Pennsylvanian cover of the dome. The sinks, containing Pennsylvanian rocks and lacking red clay, antedate that stripping.[11] Were there no caves in the region when the remarkable solution work of sink-making occurred? It is here suggested that any caves contemporaneous with the sinks must have lain in higher calcareous rock, now destroyed but at the time below that early water table. The sinks were formed at great depths, below the level of most of the active ground-water circulation.

At least three hematite mines have had a central core of sandstone, with the ore body annular about it. Structurally, this sandstone is only the youngest remaining rock involved in the subsidence. But the preferred theory must provide a specific reason for its persistence through the process of replacement. Similarly, the survival of the slab of sheared sandstone in Moselle No. 10 ore body needs specific explanation.

Caprock is mentioned by a few students of the filled sinks. Is it more than a projecting ledge *in situ*, or is it flat-lying subsided material at present surface level? The writer has seen only the latter type and the literature seems to support this interpretation. Filled caves and perhaps some circles possess a continuous cap rock in place but the sinks, by any explanation yet proposed, could not.

The writer has seen too few of the "blossom rock" type of filled sink to fit them completely into the hypothesis. Marbut and Van Horn were convinced that the sandstone fills farther north were St. Peter, Lee was sure that the blossom rocks of the Rolla quadrangle were of Pennsylvanian sandstone. The hypothesis of pre-Pennsylvanian topographic control will accept both conclusions. But if only one filled sink-making episode has occurred, some clay-filled structure might well have St. Peter sandstone beneath that clay.

Stalactitic forms, composed of pyrites and hematite, have been found in many sink fills. Fragmentary dripstone might be expected in collapsed caves, but this pipe-ore is no kin to cave stalactites. Sparingly present in sinks, pipe-ore is very abundant in the secondary limonite deposits of Missouri where the pipes have grown so closely that they constitute only the grain of a continuous rock body. A common form is "wire" pipes, a tenth to a twentieth of an inch in diameter and perhaps several inches long, grouped in "massive bundles". Gravitative control during their formation is indicated by the vertical stems in undisturbed deposits. They all have or have had a central tube, but rarely can anything larger than a knitting needle be inserted in it. Individual pipes superficially resemble straw stalactites whose tube diameter is determined by that of a drop of water on the growing tip. Until it is shown that cave drip water may have its surface tension so decreased that drops with knitting needle and smaller diameters are the rule, the writer will continue to hold that pipe-ore forms are not stalactites. When their cause is understood, their presence in filled sinks may throw more light on causal conditions for the sinks themselves.

[11] Most writers have believed, with good reason, that the pyritic fill material was derived from a cover of Pennsylvanian deposits.

References Cited

Bain, H. F. (1901) *Preliminary report on the lead and zinc deposits of the Ozark region*, U. S. Geol. Survey, 22d. Ann. Rept., pt. 2, p. 144–150.

—— (1905) *Discussion*, Econ. Geol., vol. 1, p. 172.

Ball, S. H. and Smith, A. F. (1903) *The geology of Miller County*, Mo. Bur. Geol. and Mines, 2d. ser., vol. 1, 207 pages.

Branson, E. B. (1944) *The Geology of Missouri*, Univ. Mo. Studies, vol. 19, no. 3, p. 387.

Bretz, J H. (1940) *Solution cavities in the Joliet limestone of northeastern Illinois*, Jour. Geol., vol. 48, p. 337–384.

—— (1938) *Caves in the Galena formation*, Jour. Geol. vol. 46, p. 828–841.

Bridge, J. and Charles, B. E. (1922) *A Devonian outlier near the* crest of the Ozark uplift, Jour. Geol., vol. 30, p. 450–453.

Broadhead, G. C. (1874) *Report of the Geological Survey of the State of Missouri*, p. 334 and 338.

Buehler, H. A. (1939) *"Filled sink" or "cave" deposits in the Ozark region*, Kans. Geol. Soc., Guidebook, 13th Ann. field conf., p. 138–140.

Crane, G. W. (1912) *The iron ores of Missouri*, Mo. Bur. Geol. and Mines, 2d. series, vol. 10, 434 pages.

Dake, C. L. (1935) *Basal Pennsylvanian transgression in the Ozarks*, Geol. Soc. Am., Bull. vol. 46, p. 697–714.

Fenneman, N. M. (1936) *Cyclic and non-cyclic aspects of erosion*, Sci., vol. 83, p. 87–94.

Fowke, G. (1922) *Archaeological investigations*, Smithsonian Inst., Bur. Am. Ethnology, vol. 76.

Grawe, O. R. (1945) *Pyrites deposits of Missouri*, Mo. Geol. Survey and Water Resources, 2d. ser. vol. 30. 482 pages.

—— and Cullison, J. S. (1931) *A study of the sandstone members of the Cotter and Jefferson City formations at Rolla, Missouri*, Jour. Geol., vol. 39, p. 305–330.

Hinds, H. (1912) *Coal deposits of Missouri*, Mo. Bur. Geol. and Mines, 2d. ser., vol. 11, 503 pages.

Kansas Geol. Soc. (1941) *Paleozoic rocks of central and northeastern Missouri*, Guidebook, 15th Ann. field conf., p. 19–20.

Keller, W. D. (1944) In *"The Geology of Missouri"* by E. B. Branson, Univ. Mo. Studies, vol. 19, no. 3, p. 376–383.

Lee, W. (1913) *The geology of the Rolla quadrangle*, Mo. Bur. Geol. and Mines, 2d. ser., vol. 12, 111 pages.

McQueen, H. S. (1943) *Geology of the fire clay districts of east central Missouri*, Mo. Geol. Survey and Water Resources, 2d. ser., vol. 28, 250 pages.

Marbut, C. F. (1907) *The geology of Morgan County*, Mo. Bur. Geol. and Mines, 2d ser. vol. 7, 97 pages.

Mather, W. B. (1946) *The mineral deposits of Morgan County*, Mo. Geol. Survey and Water Resources, Rept. of Investigations, no. 2.

Meek, F. B. (1855) *Report on Moniteau County*, Mo. Geol. Survey, 1st and 2d. Ann. Repts. pt. 2, p. 96–119.

Nason, F. L. (1892) *A report on the iron ores of Missouri*, Mo. Geol. Survey, vol. 2, 366 pages.

Peach B. N., Horne, J. E. *et al* (1907) *Geological structure of the Northwest Highlands of Scotland*, Geol. Survey Great Britain, Mem., p. 169 and 263.

Purdue, A. H. and Miser, H. D., (1916) *Description of the Eureka Springs and Harrison quadrangles, Ark.-Mo.*, U. S. Geol. Survey, Geol. Atlas, folio 202, 22 pages.

Pumpelly, R. (1886) *Report on mining industries of the United States*, U. S. 10th Census, vol. 15, p. 3–36.

Schmidt, A. (1872) *The iron ores of Missouri*, Mo. Geol. Survey, Prelim Rept., pt. 1, p. 45–214.

—— (1874) *The lead and zinc regions of southwest Missouri*, p. 381–502 and *The lead region of central Missouri*, p. 503–577, Mo. Geol. Survey Rept., Field work of 1873–1874.

Siebenthal, C. E. (1905) *Structural features of the Joplin district*, Econ. Geol., vol. 1, p. 119–128.

Smith, W. S. T. and Siebenthal, C. E. (1907) *Description of the Joplin district, Missouri-Kansas*, U. S. Geol. Survey, Geol. Atlas, folio 148, 20 pages.

Tarr, W. A. (1918) *The barite deposits of Missouri and the geology of the barite district*, Univ. Mo. Studies, vol. 3, no. 1, 111 pages.

—— (1937) *Origin of the marcasite sink hole deposits of central Missouri*, Am. Mineral., vol. 22, no. 7., p. 830–841.

Van Horn, F. B. (1905) *The geology of Moniteau County*, Mo. Bur. Geol. and Mines, 2d. ser., vol. 3, 104 pages.

Wheeler, H. A. (1896) *Clay deposits*, Mo. Geol. Survey, vol. 11, 622 pages.

Winslow, A. (1894) *Lead and zinc deposits*, Mo. Geol. Survey, vol. 7, sec. 2, 763 pages.

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MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, APRIL 21,1949

AIRBORNE MAGNETOMETER AND GEOLOGICAL RECONNAISSANCE SURVEY MOOSEHEAD LAKE TO CHAIN OF PONDS, MAINE

Performed during 1948; Compiled April, 1949

LEGEND

SEDIMENTARY AND METAMORPHIC

- D — Moose River sandstone. Fossiliferous sandstones, minor calcareous slates, white quartzite. Lower to Middle Devonian age.
- S — Grey to pale green calcareous slates, felsitic pyroclastics. Silurian or Devonian.
- cz — Contact zone about Younger Granite. Knotty, andalusite-bearing schists and slates.
- gs — Bright green calcareous slates.
- gn — Gneiss, schist, quartzite.

IGNEOUS

- grd — Younger Granite. Probably late Middle Devonian.
- rh — Rhyolite to trachyte flows, breccias, minor intrusives (?).
- mv — Andesite to basalt flows, breccias, minor intrusives.
- Ultrabasic rocks. Pyroxenite, serpentine, talc-carbonate alterations.
- gro — Older Granite. Unconformably underlying grey slates.

SYMBOLS

- 2400 — Magnetic Intensity Contours
- County Boundary
- Geological Boundary
- ? — Probable Fault
- F — Fossil Locality
- Probable Synclinal Axis
- Probable Anticlinal Axis
- 60 / 60 — Strike and Dip of Cleavage / Strike and Dip of Bedding

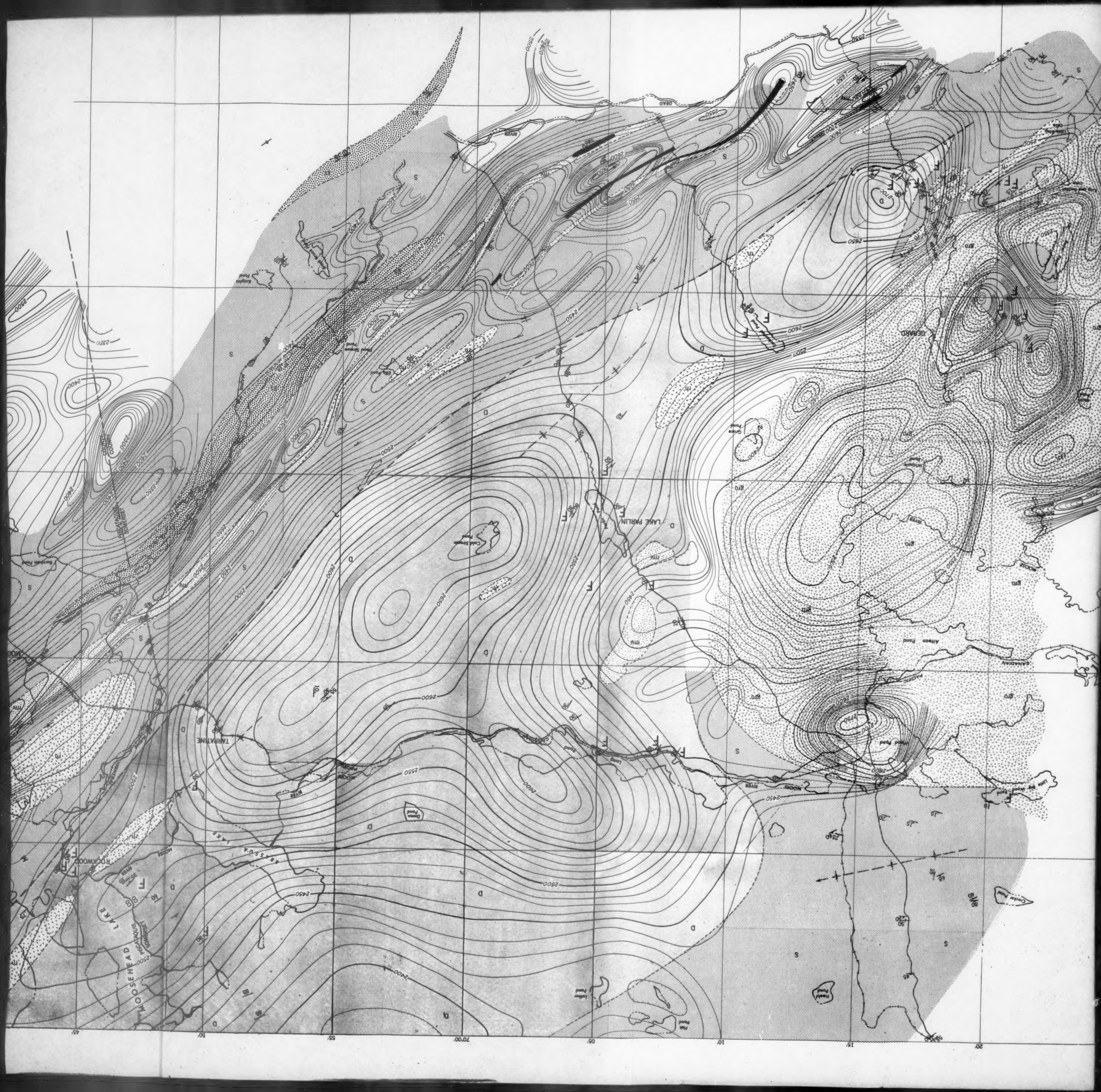
SCALE

1 0 1 2 3 4 MILES

70°40′ 35′ 30′ 25′ 20′ 15′ 10′

45°45′ 40′ 35′ 25′ 20′

Holeb Pond · Crocker Pond · Little Big Wood Pond · Big Wood Pond · Moose River · Pleasant Pond · Attean Pond · Whipple Pond · Gravel Pond · Kelly and Davidson Lake · Little Kelly Lake · Moosehead Lake · Matagamon Lake · Long Pond · Fourth Pond · Gerard · Pacific · Canadian · Somerset Tramway · County Court · Dead


LAKE PARLIN
TARRATINE
MOOSEHEAD
LAKE
ROCKWOOD
GEMMED
CANADIAN
PACIFIC
Cedar Swamp Pond
Deano Pond
Fleet Pond
Wood Pond
Albean Pond
Line of Section
70°00'
55'
50'
45'
05'
10'
15'
20'

70°00′ 05′ 55′ 50′ 45′ 40′ 35′ 69°30′ 45°45′ 40′ 35′ 30′ 25′ 20′

MOOSEHEAD LAKE
ROCKWOOD
TARRATINE
MOOSEHEAD
LAKE PARLIN
ARASSOA LAKE
KESKACHOUIS
SOMERSET
MOOSE RIVER
DEAD RIVER
Undifferentiated slates and sandstones

The magnetic survey was made by the Aero Service Corporation of Philadelphia, Pa. Variations in total magnetic intensity were recorded from a mean altitude of 1,000 feet, in parallel flight traverses spaced at

Contact zone about Younger Granite. Knotty, andalusite-bearing schists and slates.
Bright green calcareous slates.
Gneiss, schist, quartzite.

IGNEOUS

Younger Granite. Probably late Middle Devonian.
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Andesite to basalt flows, breccias, minor intrusives.
Ultrabasic rocks. Pyroxenite, serpentine, talc-carbonate alterations.
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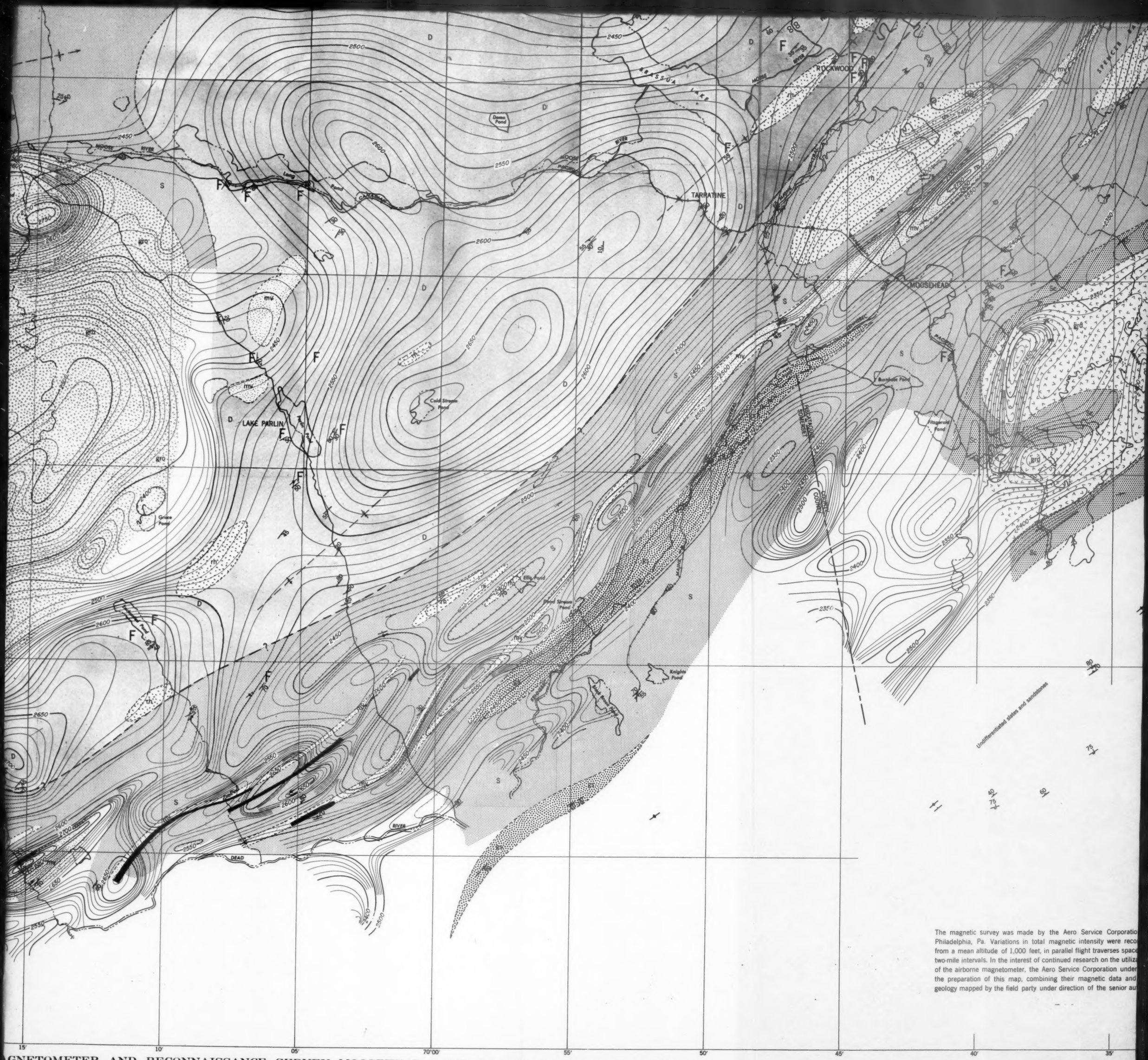
60 Strike and Dip of Bedding

SCALE

1 0 1 2 3 4 MILES

AIRBORNE MAGNETOMETER AND RECONNAISSANCE SURVEY, MOOSEH

Performed during 1948; Compiled April 1, 1949



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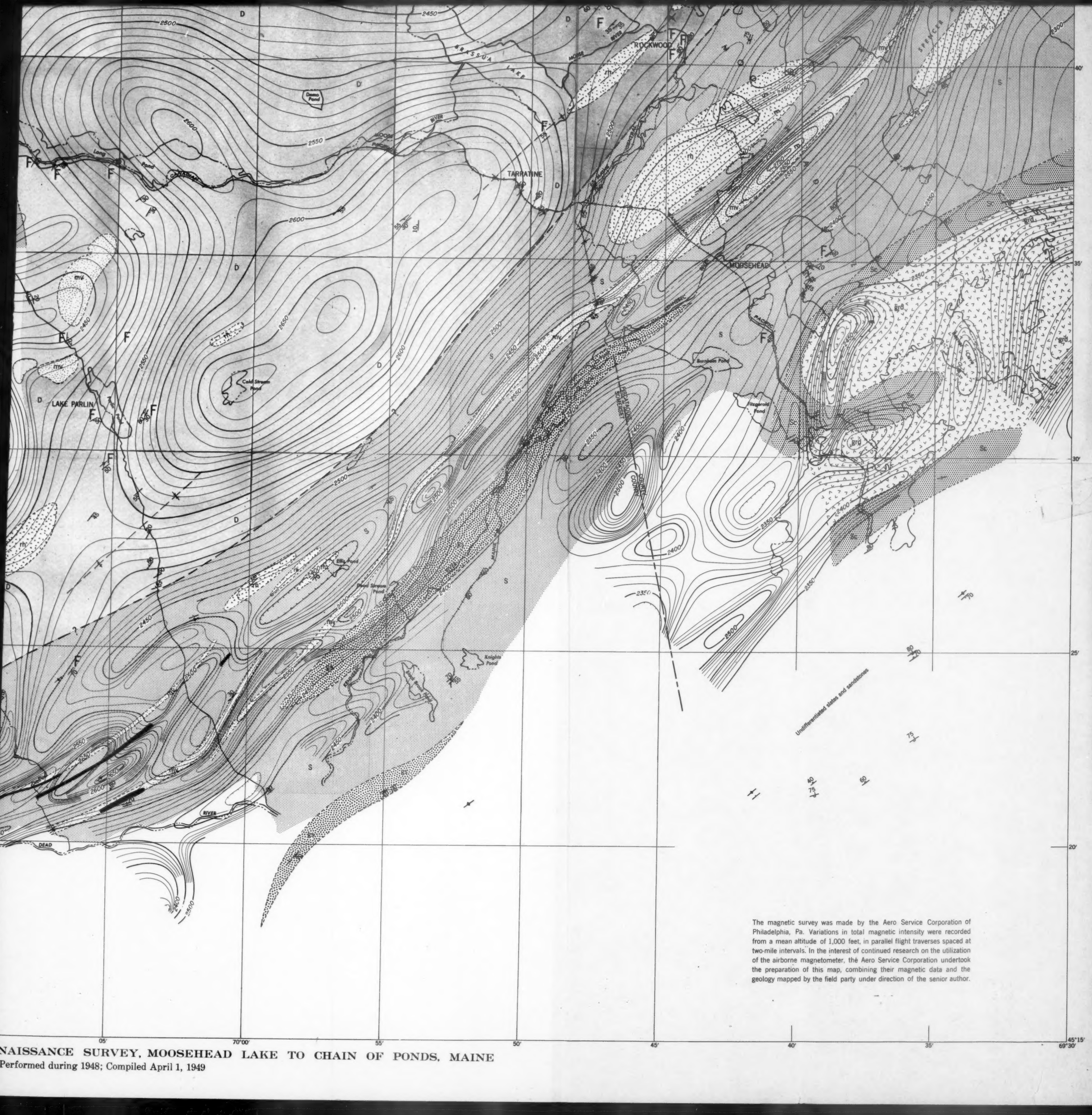
AGNETOMETER AND RECONNAISSANCE SURVEY, MOOSEHEAD LAKE TO CHAIN OF PONDS, MAINE

Performed during 1948; Compiled April 1, 1949


BRASSUA LAKE
TARRATINE
ROCKWOOD
MOOSEHEAD
LAKE PARLIN
SPENCER
Undifferentiated slates and sandstones
The magnetic survey was made by the Aero Service Corporation of Philadelphia, Pa. Variations in total magnetic intensity were recorded from a mean altitude of 1,000 feet, in parallel flight traverses spaced at two-mile intervals. In the interest of continued research on the utilization of the airborne magnetometer, the Aero Service Corporation undertook the preparation of this map, combining their magnetic data and the geology mapped by the field party under direction of the senior author.

NNAISSANCE SURVEY, MOOSEHEAD LAKE TO CHAIN OF PONDS, MAINE

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VOL. 61, PP. 835-842, 1 PL. AUGUST 1950

AIRBORNE MAGNETOMETER AND GEOLOGICAL RECONNAISSANCE SURVEY IN NORTHWESTERN MAINE

BY PATRICK M. HURLEY AND JAMES B. THOMPSON

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ABSTRACT

An airborne magnetometer survey was made in conjunction with a mineral survey in several townships in the northwestern part of Maine. The resulting geological map (Pl. 1) with superimposed total magnetic intensity variations is presented as a correlation of the character of magnetic response with different rock types in an area of widely diversified geologic features, such as is commonly the case in areas of mineral deposition. Additions and modifications were made to the knowledge of the geology of the area, the most interesting of which was the placing of a large area of granite unconformably below a section of Siluro-Devonian sediments.

ACKNOWLEDGMENTS

The field party consisted of Mr. Frank C. Canney and Mr. David L. Kendall of the Geology Department of the Massachusetts Institute of Technology, and the authors. Mr. Arthur Boucot of the Geology Department of Harvard University studied the fossils from the localities indicated on the map, and contributed information on the area in the vicinity of Parlin Pond and general information on the stratigraphy of the Moose River sandstone. The magnetic survey was carried out by the Aero Service Corporation of Philadelphia, who also, in the interest of furthering studies of aerial magnetics, generously undertook the drafting of the combined map. The authors wish also to thank Dr. J. M. Trefethen and Mr. L. Wing of the Maine Geological Survey for interesting discussions on the geology of this region.

MAGNETOMETER SURVEY

The increased demand for asbestos, and active prospecting on an occurrence south of Spencer Lake in Maine, brought about interest in a belt of ultramafic rocks, in that region, that had never been mapped.

Tests indicated that the magnetic susceptibility of the serpentines, particularly in the vicinity of asbestos mineralization, was large compared to the sediments and volcanics in which they occurred. This and the fact that most of the area was heavily drift covered brought about the decision to fly a magnetometer over the region as a means of reducing the area to be prospected. The area of interest was prescribed by land titles, so that the objective was the possible extension of the serpentine belt into this area, rather than the serpentine belt as a whole.

The magnetometer survey party consisted of a pilot, copilot, and magnetometer operator. A twin-engine plane equipped for this work with strip camera and a Gulf high-sensitivity airborne magnetometer was used. The general trend of the geologic structures was known to be northeast-southwest, and traverses were planned at right angles to this for best coverage. Roughness of terrain demanded a higher survey altitude than usual, and a mean level of 1,000 feet above drainage was decided upon. Often mineral surveys are flown at 500 feet, and sometimes as low as 300 feet. Budget limitations

and the expected continuity of the ultramafic bodies led to a decision to use wide spacing—2 miles between the traverse lines—rather than the quarter-mile traverse common to some types of mineral surveys. Variations in total magnetic intensity as small as two gammas were recorded in a continuous trace, and compiled later into magnetic intensity contour maps. Although the flying took place in May, the preliminary maps were delivered by the first week in June in time for planning and field use. About 2,000 square miles were covered in the magnetometer survey, with a total cost of less than $10,000.

Following the magnetic survey, the authors spent 3½ months in the field, covering the terrain by jeep, canoe, and on foot. An area of more than 1200 square miles was explored in a manner that satisfied the authors that nothing of economic significance had been missed. This was possible only by the use of the magnetic map, which proved to be ideal for blocking out areas that could be eliminated with a few traverses, and concentrating the time on areas that needed it. All the strong magnetic gradients on the sheet were explained by magnetic concentrations which were detected by testing rock samples with an Alnico No. 5 magnet. The magnetic data were transferred at the outset to U. S. Geological Survey 15′ topographic sheets, and geology maintained on these from the notebooks, so that at all times the correlation between rock formations and magnetic variation was in view. It soon became possible to predict the location of contacts and dikes ahead of the field survey by extrapolating the magnetic correlations, greatly reducing mapping time.

It also turned out that the highest magnetic anomaly on the sheet occurred above the asbestos occurrence on Little Spencer Stream, at 45° 20′N, 70° 15′W. In the same belt, other highs coincided with bodies of ultramafic rock carrying no significant asbestos. Some of these bodies were bordered by zones of talc-carbonate. At least two of these zones were more than 100′ wide, with a talc content that may be of future economic interest. One of these zones occurs at 45° 15′ N. and 70° 29′ W. near the road by Jim Pond; the other at 45° 21′ N. and 70° 7′ W. on Enchanted Stream.

The purpose of this paper is to make available in the literature the new additions to the geology of this region, and also to present a magnetic map correlated with it (Pl. 1). There is a fairly definite difference in the character of magnetic variations over the four principal geologic blocks—the areas of gneiss, granite, homogeneous sediments, and stratified mixed sediments and igneous rocks.

In the area underlain by gneiss, the concentrations of magnetite probably tend to follow the warped bedded structures of the gneiss. These structures were not mapped in detail, but there appears to be a principal broad anticline that curves from a northeasterly direction to a northerly one, proceeding north. The principal magnetic trend follows this pattern, with a fair degree of correlation between magnetic contours and strike of bedding. To the west of this strip, the structure shows sharp changes of strike with moderate dips, again paralleled to some extent by the magnetic contour lines. The area has been deeply cut by the drainage. The overall result of the occurrence of magnetite in dissected curved planes is to cause magnetic contour shapes tending to intricate and continuing convolutions.

In contrast with this, the non-laminated granites, with their more equidimensional concentrations, produce more closed contour patterns of a "bird's-eye maple" appearance.

The lack of any sharp gradients in the block of Moose River sediments in the central part of the map is characteristic of this formation over the entire area in which these sediments occurred. The magnetic contours conform almost identically with the dikes in the belt of mixed sedimentary and igneous rocks referred to as Siluro-Devonian, and were most useful for plotting the location of the intruded masses beneath the overburden.

Magnetization of Asbestos-Bearing Serpentine

The clearly defined anomaly on the asbestos-bearing serpentine on Spencer Stream was analyzed for general information on the magnetization of this type of alteration zone. Several dip-needle traverses across the zone sharply outlined the width of the ultramafic mass, giving an average value of about 450 feet in the central section on the east side of

Little Spencer Stream. Magnetite was concentrated somewhat toward the northern edge, but for this analysis was assumed to be uniformly disseminated over the entire width. A theoretical total intensity curve was found to match the observed central profile quite closely on the basis of a semi-infinite dike striking N 55° E, dip 75° NW, and width of 450 feet; flight altitude of 1300 feet; magnetic declination N 15° W; and increase of magnetization of mass above surroundings, $\Delta I = .006$ c.g.s. units. Any permanent magnetization was assumed to be parallel to the earth's field, and demagnetization was disregarded.

The overall value of .006 discovered for ΔI seemed low, considering the strong pulls detected on the hand magnet on several specimens. However, these specimens were chosen mainly from outcrops showing asbestos, so were not representative of the mass as a whole. The background level of the region seems to have been comparable to common values for granite, so that on the basis of I (total) = .008 it would appear that the amount of magnetite in the ultramafic was not above 5 per cent, unless permanent magnetization contributed in the negative direction. This figure is based on a susceptibility for magnetite in a rock of .003 c.g.s. units per per cent of magnetite.

In the Thetford district, Quebec, it was found that the pull on an Alnico magnet when testing specimens of serpentine increased from weak to strong as deposits of asbestos were approached, and underground in a working mine the magnet would hang to the walls in places. The serpentine exhibited a high susceptibility even away from any chrysotile veinlet. In general it was found that almost any rock causing a local magnetic variation of over 100 gammas at normal flight altitude would exert a detectable pull on the Alnico magnet, so that magnetic susceptibility could be readily gauged in the various rocks underlying magnetic areas of interest.

Geology

Previous Work

It was recognized at the time of the early state surveys that this area contained fossiliferous Paleozoic sediments in addition to a variety of eruptive rocks. Many of the fossil localities were first described in the reports of the Jackson Survey between 1837 and 1839. C. H. Hitchcock (Hitchcock and Holmes, 1861–1862) described additional fossil localities and dated the fossiliferous rocks as Siluro-Devonian. A later paper (Hitchcock and Huntington, 1874) described the sediments in more detail and mentioned gneisses underlying them unconformably on the west.

The Moose River sandstone (Williams and Gregory, 1900) was first described in detail by J. M. Clarke in his "Early Devonic History of New York and Eastern North America" (1909). E. H. Perkins (1925) discussed the relationship of the Moose River to some of the surrounding rocks, and E. S. C. Smith in a series of papers (1925; 1929; 1933) described a number of rhyolite bodies associated with the sandstone. Perkins also noted an occurrence of a Silurian graptolite in the slates bordering the Moose River sandstone on the northwest and named the formation the Seboomook slate. A series of sediments and volcanic rocks outcropping in the Ripogenus Dam area has been designated the Ripogenus series (Toppan, 1932), and the fauna of the Chesuncook limestone of that series identified as Niagaran (Willard, 1945).

The plutonic rocks of the area have received somewhat less attention. Hitchcock and Huntington considered the granitic rocks west of the Moose River sandstone and those in the vicinity of Mt. Bigelow to be older than the Moose River sandstone, but were not explicit concerning those in the Moosehead Lake area. Philbrick (1936; 1940) has shown that the granites of Moosehead Lake and the regions immediately to the southeast are intrusive into sedimentary rocks of probable Silurian age. On the state map (Keith, 1933) all of the granitic rocks of the area are shown as Devonian or Carboniferous and presumably younger than the Silurian and Lower Devonian sediments.

Present Investigation

Any interpretation based upon the present reconnaissance must be considered tentative. A major unconformity was found, however, separating the Siluro-Devonian rocks from the area of granite (and gneiss) bordering them on

the west, and numerous new fossil localities were discovered, several of them in areas shown as granite on the present state map.

The Moose River formation is dominantly a gray or buff-weathering sandstone with an abundant fossil fauna indicating a Lower Devonian (Oriskany-Onondaga) age. Gray, sandy slates occur interbedded with the sandstones and in some areas are more abundant than the sandstones. A few beds of impure limestone not more than a few inches thick have been found associated with the slates. Much of the sandstone is conspicuously cross-bedded. This and a well-developed cleavage in the more argillaceous beds make determination of tops and bottoms relatively easy in regions of steep dips. Several sizeable bodies of rhyolite and diabase have been mapped separately and may be either sills or flows.

The Moose River sandstone occupies a broad syncline plunging gently to the northeast. The dips northwest of the major synclinal axis are variable because of minor folds, but are consistently steep on the southeastern limb varying from 60° northwest to nearly vertical. There is evidence that the syncline is bordered on the southeast by a major thrust fault. In the vicinity of Moosehead Lake, the Moose River sandstone on the southeast limb appears to be too thin, and in the vicinity of Enchanted Pond and Spencer Lake the southeast limb of the syncline may be entirely absent. Highly sheared rocks were observed in the vicinity of Tarratine and about the foot of Spencer Lake. It is possible that the valley along the southeastern border of the Moose River sandstone from Tarratine southwest along Churchill and Chase streams may follow a zone of shearing.

The Seboomook slate, bordering the Moose River sandstone on the northwest, is a dark-gray slate with minor beds of sandstone. If the graptolite found by Perkins is a valid indication, at least part of the formation is of Silurian age. The contact with the Moose River sandstone as exposed along the road north of Rockwood appears to be conformable and gradational. The argillaceous beds in the Moose River sandstone seem to become more abundant northward until the rock is indistinguishable from the Seboomook slate.

A highland area trending east-northeast borders the Seboomook slate on the north beyond the limit of the map. Very few observations were made in this area. The rock types noted included green slate, gray slate, and greenstone. Their relationship to the Seboomook slate is not known. These rocks extend west into the Risborough-Marlow area of Quebec (Faessler, 1939) where they are mapped as the Frontenac formation, believed to be largely of volcanic origin. The pillow lavas and associated pyroxene-rich gabbro of the region about Canada Falls Deadwater are probably a part of this same belt. North of this highland area are more gray slates with interbedded sandstones and a few beds of impure limestone. These have been mapped as the Compton formation by Faessler. In adjacent regions of Quebec, the names Beauceville (Lord, 1938) and St. Francis (Cooke, 1937; 1947a; 1947b) have been used for the same rocks which have been considered of Ordovician age. In a series of new road cuts on Rte. 201 just south of the international boundary, however, cross-bedded sandstones are exposed bearing a marked lithologic resemblance to the Moose River sandstone, but containing no fossils. Faessler considered the Compton and Frontenac formations to be separated by an unconformity, and considered the Frontenac to be of Cambrian or Precambrian age. McGerrigle (1935) and Lord (1938) considered the Frontenac formation to be of Cambrian or Ordovician age.

On the north shore of Little Big Wood Pond in Dennistown, limestone and calcareous slate are underlain by arkose and conglomerate with a fossiliferous limy matrix resting unconformably upon altered gneissic granite. The series dips northward beneath the Seboomook slate. A similar series of fossiliferous calcareous and conglomeratic rocks occurs in an isolated patch west of the northern end of Spencer Lake. Pebbles of the underlying granitic rocks are abundant in the conglomerates. They appear again west of the southern end of Spencer Lake in the vicinity of Bear Pond. At this locality they dip south and are overlain by calcareous slates, rhyolite, and rhyolite tuff, more calcareous slates, and finally, near the foot of Spencer Lake, by typical fossiliferous Moose River sandstone. The approximate thicknesses (assuming no major duplication) in this section

are 3000 feet for the conglomerate, limestone, and lower calcareous slate, 4500 feet for the rhyolite and tuff, and 2000 feet for the upper calcareous slate. In the vicinity of Parlin Pond, a thickness of about 6000 feet of Moose River sandstone is exposed, but the formation is undoubtedly much thicker. It is interesting to contrast the Spencer Lake section with the apparent stratigraphic succession farther north. The possible equivalent of the Seboomook slate is here in large part rhyolite and rhyolite tuff. Fossiliferous limestones resembling those of the Bear Pond locality are found to the southwest at Jim Pond and Little Jim Pond.

The Moose River sandstone is bordered on the southeast by a belt 6–8 miles wide of varied lithologic character and uncertain structure extending from Jim Pond and Eustis townships northeast to the Ripogenus Dam area. The dominant rock types are gray calcareous slates and felsitic flows and pyroclastics. Fossiliferous limestones associated with arkose or conglomerate are also common. They have been found west of Little Spencer Stream about midway between Spencer Lake and Spencer Stream itself; on the southwest shore of Moosehead lake just north of the base of Squaw Mountain; on the east side of Deer Island and the southeast shore of Spencer Bay, Moosehead Lake; south of Ragged Lake on the road from Kokadjo to Ripogenus; and at Ripogenus Dam. Fossiliferous limestone was found on the top of Limestone Hill, Flagstaff, and has previously been reported (Hitchcock and Huntington, 1874) to outcrop on an island in Flagstaff Pond. Fossiliferous calcareous shales were found in the northeastern corner of Lower Enchanted township and in a roadcut about a mile southwest of Kokadjo. It is probable that the calcareous rocks as well as several extensive bands of rhyolite and rhyolite tuff belong to the Ripogenus Series. A few minor beds of red and green slate have been included with the above on the map, but between the Forks and Moosehead Lake, two bands of conspicuous bright-green calcareous slate have been mapped separately. A band of predominantly mafic volcanics has also been mapped separately. In the vicinity of this band, there are a few small, concordant bodies of peridotite, pyroxenite, and gabbro.

Southeast of this complex belt, the country is underlain by a monotonous series of dark slates and sandstones extending an unknown distance to the southeast. The black slates of the Monson area are a part of this series. On the basis of poorly preserved graptolites from Brownville (Smith, E. S. C., 1929), the slates of the Monson belt have been considered Silurian. Some of the cross-bedded sandstones outcropping along Rte. 201 north of Bingham resemble those of the Moose River. About the southern tip of Moosehead Lake, at Moxie Bald Mountain and at Bigelow Mountain, these sedimentary rocks have been converted to andalusite schists forming contact aureoles about a series of granitic stocks. Two of these aureoles have been described elsewhere (Philbrick, 1936; 1940). As this contact metamorphism has affected rocks mapped as part of the Ripogenus series near the southern end of Moosehead Lake, the granites are believed to be younger than the Siluro-Devonian sediments.

The rocks underlying the Siluro-Devonian sediments unconformably on the west are largely granitic with minor amounts of diorite and gabbro. All of these rocks are highly altered, however, in marked contrast to the granitic rocks about the foot of Moosehead Lake. The ferromagnesian minerals are largely altered to chlorite and the plagioclases to a conspicuous green saussurite. The granite is generally porphyritic with ovoids up to 2 inches long of pink potash feldspar, much of it showing a rapakivi-type zoning.

The older granites are bordered on the west by a large area of gneiss, apparently of sedimentary origin. The relationship of the gneiss to the older granite is not known. Along Rte. 4, however, by the northwesternmost of the Chain-of-Ponds, the gneisses are clearly cut by fresh-looking granite which extends northwest to the international boundary. This granite is apparently continuous with the Spider Lake granite of Lord (1938), mapped as of probable Devonian age. It resembles the granitic rocks of the Moosehead Lake area more closely than the older granites about Jackman and Spencer Lake. The area of gneissic rocks includes feldspathic quartzites and a few chlorite and hornblende schists. Some of the rock appears to be a metamorphosed conglomerate or breccia.

Limited structural observations suggest a broad, archlike anticline.

The rocks of known or probable Siluro-Devonian age in the area have not suffered much metamorphism except in the vicinity of the granitic rocks at the southern end of Moosehead Lake. Slaty cleavage is well developed in all of the argillaceous rocks, but bedding and other primary features are in general well preserved. The mafic volcanics in the belt southeast of the Moose River sandstone appear more altered than the enclosing sediments and are now in large part typical "greenstones" although still showing good pillow structures. The rhyolites of the same area are conspicuously sheared, some of them approaching sericite schists. The rhyolites in the Moose River sandstone, on the other hand, are comparatively fresh and have a flinty appearance. The ultramafic rocks are largely serpentinized and some of them are bordered by talc-carbonate zones.

Paleontology

Unfortunately, it was not possible to make adequate fossil collections from any of the fossil localities shown on the map during this investigation. Most of the specimens brought back were either non-diagnostic or too poorly preserved to be of much use. As information on the area is so sparse, however, all localities where fossiliferous rocks were observed in the field have been shown on the map, even though no specimens were collected.

The following list of genera, identified by Mr. Boucot, is included in the hope that it may be of some use to future investigators. (Only fossils from rocks other than the typical Moose River sandstones are listed).

At 45° 38′ N, 70° 21′ W, on north shore of Little Big Wood Pond, Dennistown:
- *Halysites*, sp.

In the area 45° 25–26′ N, 70° 20–21′ W, west of Spencer Lake:
- *Favosites* sp. (resembles Silurian species but could be lower Devonian)
- Crinoid stems
- Orthoid brachiopod

At 45° 17.5′ N, 70° 28′ W, 0.2 mi. north of Little Jim Pond outlet, Jim Pond Township:
- *Coenites* sp.
- *Heliolites* sp.
- *Halysites* sp.

At 45° 16′ N, 70° 30′ W, on northeast shore of Jim Pond, Jim Pond Township:
- *Favosites* sp. (resembles Niagaran or Helderberg species)
- Crinoid stems

At 45° 45.5′ N, 69° 22′ W, 9 mi. northeast of Kokadjo on Great Northern Paper Co. road (off map)
- *Favosites* sp. (resembles Niagaran or Helderberg species)
- *Gastropods*

At 45° 33′ N, 69° 41′ W, on the point south of Deep Cove, on the southwest shore of Moosehead Lake:
- Pelmatozoon columnals

The last is possibly the locality where J. T. Hodge (Jackson, 1838b) reported corals. Specimens from some of the other localities and from Limestone Hill in Flagstaff (Hitchcock and Huntington, 1874; Ruedemann and Smith, 1935) were too poorly preserved to be identified. All of the fossils listed above are from rocks believed to underlie conformably the Moose River sandstone and to overlie unconformably the older granites and gneisses. The rocks resemble lithologically those of the Ripogenus series which is at least in part of Niagaran age. The rocks beneath the Moose River sandstone may be continuous with the Ripogenus series, but this cannot as yet be demonstrated.

References Cited

Clarke, J. M. (1909) *Early Devonic history of New York and eastern North America*, N. Y. State Mus., Mem. 9, 250 p.

Cooke, H. C. (1937) *Thetford, Disraeli, and eastern half of Warwick map-areas, Quebec;* with chapters on the Beauceville, St. Francis and Lake Aylmer series by Thomas Henry Clark. Can. Geol. Survey, Mem. 211, 160 p.

——(1947 a) *Dudswell sheet, Quebec*. Can. Geol. Survey, Map 408-A.

——(1947 b) *Scotstown sheet, Quebec*, Canada Geol. Survey, Map 913-A.

Faessler, Carl (1939) *Risborough-Marlow Area, Frontenac County (Quebec)*, Quebec Bur. Mines, Geol. Rept. 3, 18 p.

Hitchcock, C. H. and Holmes, E. (1861) *Preliminary report upon the natural history and geology of the State of Maine*, Me. Board Agri., 6th Ann. Rept. p. 91–458

——(1862) *Second annual report upon the natural history and geology of the State of Maine*, Me. Board Agri., 7th Ann. Rept., p. 217–447.

——and Huntington, J. H. (1874) *Geology of the northwest part of Maine*, Am. Assoc. Adv. Sci., Pr., vol. 22, p. 205–214.

Jackson, C. T. (1837 a) *First report on the geology of the State of Maine*, Augusta, 1837, 128 p.

——(1837 b) *First report on the geology of the public lands in the State of Maine*, Boston, 1837, 47 p.
——(1838 a) *Second report on the geology of the State of Maine*, Augusta 1838, 168 p.
——(1838 b) *Second annual report on the geology of the public lands belonging to the two states of Maine and Massachusetts*, Boston 1838, 93 p.
——(1839) *Third annual report on the geology of the State of Maine*, Augusta, 1839, 276 p.
Keith, Arthur (1933) *Preliminary Geologic map of Maine*, Scale 1:1,000,000. Maine Geol. Survey.
Lord, C. S. (1938) *Megantic sheet, west half, Frontenac County, Quebec*, Can. Geol. Survey, Map 379A.
McGerrigle, H. W. (1934) *Mount Megantic area, southeastern Quebec, and its placer-gold deposits*. Quebec Bur. Mines, Ann. Rept., Part D, p. 63–104.
Perkins, E. H. (1925) *The Moose River sandstone and its associated formations*, Am. Jour. Sci., 5th Ser., vol. 10, p. 368–375.
Philbrick, S. S. (1936) *The contact metamorphism of the Onawa pluton, Piscataquis County, Maine.*, Am. Jour. Sci., 5th Ser., vol. 31, p. 1–40.
——(1940) *Reconnaissance of the contact metamorphism of the Katahdin and Squaw Mtn. intrusives Maine*, Am. Jour. Sci. vol. 238, p. 710–716.
Ruedemann, R. and Smith, E. S. C. (1935) *The Ordovician in Maine*, Am. Jour. Sci. 5th ser., Vol. 30, p. 353–355.
Smith, E. S. C. (1925) *The igneous rock of Mt. Kineo and vicinity*, Am. Jour. Sci., 5th Ser., vol. 10, p. 437–444.
——(1929) *New Fossils from Maine*, Sci., n.s., vol. 70, p. 168–169.
——(1933) *An occurrence of garnet in rhyolite*, Am. Jour. Sci., 5th Ser., vol. 25, p. 225–228.
Toppan, F. W. (1932) *The geology of Maine*, Dept. of Geology, Union College, Schenectady, N. Y., 141 p.
Willard, Bradford (1945) *Silurian Fossils from Ripogenus Dam, Maine*, Jour. Paleon., vol. 19, #1, p. 64–68.
Williams, H. S. and Gregory, H. E. (1900) *Contributions to the geology of Maine*, U. S. Geol. Survey, Bull. 165, 212 p.

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VARIATION OF ELASTIC MODULI OF IGNEOUS ROCKS WITH PRESSURE AND TEMPERATURE*

By D. S. Hughes and H. J. Jones

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Abstract

Using pulse methods recently developed, direct measurements of the dilatational and rotational elastic wave velocities in igneous rocks were made. D. C. pulses, impressed on 5 MC X-cut piezoelectric quartz crystals, were used to excite sharp, elastic pulses in rocks. The amplified output of similar detector crystals was studied and photographed using suitable oscilloscopes. Two main arrivals of energy were precisely timed, and from the travel times the dilatational and elastic velocities were computed. Velocities were measured with an accuracy greater than 1 per cent. Regarding rocks as homogeneous, isotropic media, the elastic constants were computed from the velocity data. The sample assembly was placed in a pressure cell, surrounded by an oil bath; thus measurements at high pressures and temperatures could readily be made. Measurements were made in the pressure range 1–1100 kg./cm.² and the temperature range 30–150°C. Samples of granite, quartz monzonite, diorite, andesite, and norite were investigated.

Materials were studied both while enclosed in impervious copper jackets and while exposed to the fluid pressure medium. The enclosed samples had relatively great increases of velocity with pressure at the low pressures, presumably due to closing of initial pore space; the rate of increase became small and essentially linear at higher confining pressures. Open samples had small, linear rates of increase of velocity over the entire pressure range. Pressure increase was accompanied by increase of wave velocities and elastic constants in all cases. Increase of temperature was accompanied by decrease in velocities and moduli. Changes of Poisson's ratio with pressure and temperature were small and erratic.

The reasonably good agreement of the present work at effective frequencies of 2–6 megacycles with earlier measurements at low frequencies suggests that for rocks the effect of frequency upon

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velocity is negligible, although the data are, as yet, inconclusive. The present work has established a useful method of obtaining direct measurements of elastic wave velocities in rocks. Extension of the pressure and temperature ranges should provide data valuable for comparison with earthquake seismic results for the earth's crust.

Introduction

Two factors complicate the laboratory measurement of wave velocities and elastic moduli of rocks. First, ordinary rock is generally a complex mixture of different crystals and has a very low tensile strength. In the laboratory under atmospheric pressure it is released from its normal confining pressure, and its internal condition may be quite different from normal. Ide (1937) has shown that carrying a granite sample through a temperature cycle of 180°C caused a marked hysteresis in its physical properties. The rock can be restored to approximately natural conditions by subjecting it to uniform hydrostatic pressure. This, however, introduces a second difficulty. The wave velocity is usually measured by finding the resonant frequencies of cylinders of the materials. The dilatational resonant modes of vibration of short, thick cylinders are not thoroughly known. If long, thin cylinders are used the frictional losses due to the confining fluid are so high that the modes cannot be identified. Birch (1940; 1943; Birch and Bancroft, 1938) has succeeded in measuring the rotational velocities under these conditions by using nitrogen as the confining fluid.

An elastic wave, incident on the boundary between two media, gives rise not only to reflected and refracted waves of the same type but, in general, to waves of other types also. Thus, an incident, dilatational wave gives rise usually to reflected and refracted dilatational waves and reflected and refracted rotational waves (Grammel, 1928).

This transformation in type has been found necessary in the explanation of earthquake seismograms for many years and has also been observed under laboratory conditions (NDRC, 1946). The complete system of waves is usually extremely complicated. However, a particularly simple result is obtained if a short, plane dilatational pulse travels parallel to the axis of a circular cylinder (Hughes, *et al.*, 1949).

This pulse gives rise at the boundary to rotational pulses which leave the boundary at the critical angle given by

$$\sin \theta = \frac{V_R}{V_D} \tag{1}$$

where V_R is the velocity of rotational waves in the medium and V_D is the velocity of dilatational waves. This pulse ultimately reaches the opposite boundary and gives rise to a dilatational pulse traveling parallel to the axis and a reflected rotational pulse traveling at the angle θ to the axis. Thus, if the rod is sufficiently long, the original dilatational pulse is followed by an evenly spaced series of similar pulses. The time interval between successive pulses is easily shown to be (Hughes *et al.*, 1949)

$$\Delta t = \frac{D[V_D^2 - V_R^2]^{\frac{1}{2}}}{V_D V_R} \tag{2}$$

where D is the diameter of the cylinder and V_D and V_R are as defined. Thus if the length of the rod is L and allowing for reflections at the opposite end, a pulse incident on one end of the rod at $t = 0$ may be expected to result in pulses arriving at the opposite end at times indicated by the following equation

$$t_{nm} = m\Delta t + n\frac{L}{V_D} \tag{3}$$

where m is any integer 0, 1, 2, . . . , and n is any odd integer 1, 3, 5, . . . , and m and n are subject to the condition

$$n\,L \geq m\,D \tan \theta \tag{4}$$

For metal rods values of n up to 15 and values of m up to 7 have been observed. Under these conditions highly accurate values of V_D and V_R can be computed.

With rocks, only arrivals given by $n=1$, $m=0$, and $n=1$, $m=1$ have been definitely identified. These will be referred to as the 10 and 11 arrivals. This is sufficient to enable V_D and V_R to be computed with somewhat reduced accuracy.

In addition to permitting both velocities to be obtained from a single measurement, this method has the further advantage that the pulse transmission is not sensitive to the boundary conditions. Thus, placing the sample in an oil bath causes no detectable change. Increas-

ing the pressure usually improves the quality of the transmitted pulse. For most rocks the 11 arrival cannot be read until a pressure of about 500 p.s.i. is reached.

5.0 MC x-cut quartz crystals 1 inch in diameter. Pulses with a rise time of about .10 μsec. and 800 volts amplitude are used. The time of arrival of a pulse within the range of

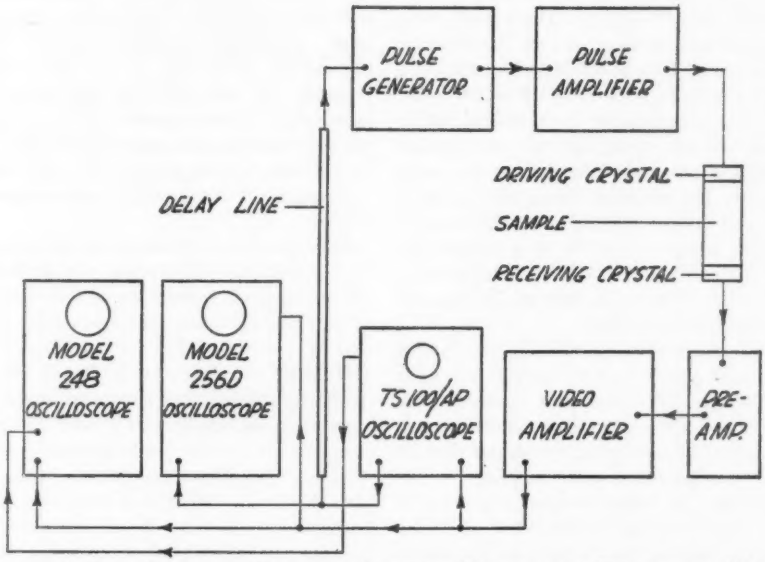

FIGURE 1.—BLOCK DIAGRAM OF ELECTRONIC APPARATUS MODIFIED FROM HUGHES ET AL. (1949)

The 10 arrival permits V_D to be determined directly, then from the 11 arrival Δt is computed, substituting V_D and D, in equation (2) the rotational velocity is computed. The ordinary formulae for these velocities may be solved for the elastic constants, then

$$\mu = \rho V_R^2 \tag{5}$$

$$k = \rho V_D^2 - (4/3)\mu \tag{6}$$

$$\sigma = [\tfrac{1}{2}(V_D/V_R)^2 - 1]/[(V_D/V_R)^2 - 1] \tag{7}$$

where ρ is the density of the material
μ is the rigidity modulus
k is the bulk modulus and
σ is Poisson's ratio

APPARATUS

Hughes *et al.* (1949) have described the electronic apparatus for generating the pulses and measuring the transmission time. A few recent modifications have been made (Hughes *et al.*, 1950). The pulses are applied to the rock at one end and detected at the opposite by means of

3–600 μsec. after the initial can be measured with an accuracy of .05 μsec. for materials with good transmission. The pulses transmitted by the rocks are not very sharp, but, even here, an accuracy of .10 μsec. can usually be achieved.

The basic instrument is a TS-100/AP circular-sweep oscilloscope (Fig. 1) with a free-running 80.86 KC circular sweep. Each revolution is, therefore, 12.368 μsec. in length. An internal trigger generator is accurately synchronized at a submultiple of 80.86 KC, usually about 200 trigger pulses per second. These pulses are very accurately synchronized to fire at the instant the circular sweep passes through zero on the screen. The trigger pulses pass internally to a delay multivibrator. The delay of this multivibrator may be varied from about 5 to 800 μsec. At the end of the delay period the circular sweep is turned on for one revolution. Thus, the time of any event impressed on the radial electrode of the tube may be timed very accurately by counting the revolutions and fractions of a revolution that it

appears after the trigger pulse. Externally, the trigger pulse is transmitted through the delay line, which delays it about 3.5 μsec., and then to the pulse generator. The pulse generator provides an output pulse accurately synchronized with the trigger. The output pulse has a rise time of about .3 μsec. Its duration may be varied from about .6 μsec. to 60 μsec., and its amplitude from about 20 to 180 volts. With metals, these pulses are sufficient, but to provide sufficient energy for rocks and similar materials a pulse amplifier follows the pulse generator. This amplifier uses a 6AG7 tube to invert and sharpen the pulse, an 807 tube as an amplifier, and a second 807 as a cathode follower for an output tube. This amplifier provides pulses with a rise time of .2 μsec. and about 800 volts amplitude.

These pulses are impressed on the driving crystal and generate a very sharp elastic wave in the sample. These waves are received at the opposite end of the sample by a similar crystal. The output of the receiving crystal goes through the pre-amplifier and main amplifier to the oscilloscope. The received signal is sent to the radial electrode of the TS-100/AP as all precise times are read on this instrument. The distortion inherent in the circular sweep, however, makes it desirable to check the wave form with a linear display. For this purpose the 256-D oscilloscope is used. It may also be used for fairly accurate time measurements. The 248 oscilloscope is used principally for photographing wave trains. It is equipped with fixed sweeps of 5, 25, 100, and 1000 μsec. duration. By utilizing the delay gate of the TS-100/AP, any of the above sections of the received signal after the trigger may be displayed on the screen and photographed. Thus, for example, the portion of the signal received during the period 25 to 50 μsec. after the initial pulse may be displayed on the screen and examined in detail or photographed.

Figure 2 shows a diagram of the pressure cell and associated equipment (Hughes *et al.*, 1950). The cell is constructed of type 309 stainless steel, 4 inches in diameter and 12 inches high. The inner chamber is 2 inches in diameter and 7 inches high. The cell is placed in a brass tank filled with SAE 30 motor oil and fitted with stirrer, heater, and cooling coils. The electrical leads are brought out through the head of the chamber.

Porosity of rocks causes a complication. In igneous rocks this probably arises because the component crystals which fitted each other under the conditions of formation no longer fit under laboratory conditions, giving rise to microscopic cracks and pores. Thus, in the pressure cell the fluid will penetrate these spaces, and the fluid pressure will be exerted on the individual crystals rather than on the rocks as a whole. A more detailed discussion of the consequence of this structure is given in a later section.

It is thus necessary to enclose the specimen in a jacket that will transmit the hydrostatic pressure but will exclude the oil from the pores of the rock. This effect was observed by Adams and Williamson (1923) and by Birch (1943) and Birch and Bancroft (1938). Adams and Williamson found that specimens enclosed in impervious jackets showed greater changes of compressibility under low hydrostatic pressures than did unenclosed specimens. They concluded that the difference in behavior could be attributed to porosity in the rocks and also possibly to differential compression of the several constituents of the rock. Birch and Bancroft reached similar conclusions.

Thus in order to obtain measurements of the elasticity of a rock sample considered as a unit, it is necessary to enclose the specimen in a jacket that will transmit the hydrostatic pressure but will exclude the oil from the pores of the rock. Adams and Williamson employed soldered tin jackets; Birch and his associates found that seamless copper tubes with copper endcaps soldered on were most efficient. Sprayed lead coats were very successful in blocking penetration of the oil, but the poor elasticity of lead at these frequencies necessitated machining the end coating to a thickness of a few thousandths of an inch. It was very difficult to do this consistently without puncturing the jacket.

The most successful jackets have been obtained by silver soldering copper foil .010 inch thick to form a tube closely fitting the sample. This tube is carefully trimmed to the exact length of the sample, and copper foil caps .005 inch thick are soldered on.

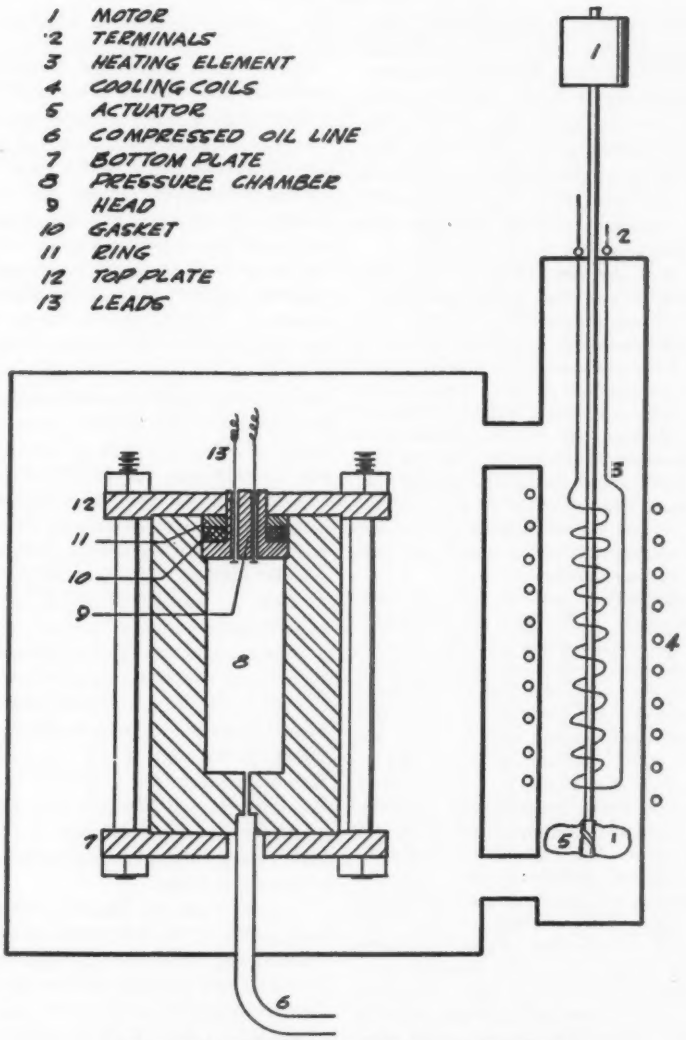

FIGURE 2.—DIAGRAM OF THE PRESSURE CYLINDER

The samples investigated have all been circular cylinders .985 inch in diameter and 2 to 4 inches in length. With very short cylinders the transmission times are so short that the accuracy is low, also the 11 arrival is very weak. This arrival becomes stronger with increasing length of transmission, but samples longer than 4.0 inches cannot be placed in the pressure chamber.

All samples were cut from solid rock by a diamond drill and cut to length by a diamond saw. The ends were ground to a plane parallel finish before measurements were made.

DESCRIPTION OF MATERIALS

Acidic, intermediate, and basic igneous rocks were investigated. Results are presented for

four granular rocks and one aphanitic type. The sample of Bear Mountain granite was obtained from the Bureau of Economic Geology of The University of Texas, and the other specimens were purchased from Ward's Natural Science Establishment, Rochester, New York. The latter are described in a well-known pamphlet by Clark (1916). The following descriptions are based upon this pamphlet plus study of thin sections.

Granite: from the Bear Mountain mass near Fredricksburg, Texas. Fine- to medium-grained, rust-colored. Essential minerals are microcline, orthoclase, acid plagioclase, quartz, and biotite. A discussion of this rock, including a chemical analysis, is available (Barnes *et al.*, 1942). Density 2.610 g/cc. This rock was evidently somewhat metamorphosed; it has been fractured and reconsolidated.

Quartz monzonite (Biotite granite): from Westerly, R.I. (No. 16 of the Clark series). Fine-grained, pink, hypidiomorphic. Essential minerals are acid plagioclase, orthoclase, microcline, quartz, biotite, and muscovite. Density 2.628. The original discussion was given by Dale (1908).

Norite (Hypersthene gabbro): from Elizabethtown, Essex Co., N. Y. (No. 50 of Clark collection). Coarse-grained, dark. Essential minerals are labradorite, hypersthene, hornblende, biotite, olivine, ilmenite-magnetite, and augite. Garnet is a common reaction product in the labradorite. Density 3.057. The original description was given by Kemp and Ruedemann (1910). A chemical analysis of this (or a similar) rock is given by Washington (1917).

Diorite: from Salem, Massachusetts. Similar to No. 39 of the Clark collection, but apparently from a different locality. Dark, medium- to fine-grained, granular. Essential minerals are zoned plagioclase (chiefly andesine and oligoclase), green hornblende, abundant augite, biotite, and some chlorite; chlorite is apparently an alteration product of biotite. Apatite and magnetite are very abundant accessories. Density 3.025; this high value undoubtedly is due to the high content of augite and magnetite. The rock is intermediate between a true diorite and a gabbro.

Andesite: from near Salida, Chaffee County, Colorado. This was listed by the collector as No. 40 of the Clark collection, but thin-section study indicates a somewhat different rock. The texture is porphyritic-aphanitic with abundant small lath-shaped phenocrysts of andesine and labradorite. Also abundant are zoned plagioclase phenocrysts and grains and crystals of clear augite. Magnetite is common. The groundmass consists mostly of glassy material, with plagioclase microlites. Density 2.618.

Presentation of Results

Tables 1 and 2 give the dilatational and rotational wave velocities of enclosed specimens of the five rock types at seven pressures and three temperatures. From them one may calculate readily the elastic moduli for a rock at a specific pressure and temperature. The tables present the velocities and elastic moduli to four significant figures, although this exceeds the accuracy of a single measurement. The absolute observational error for a single measurement is about $\pm$ .05 μsec. for the 10 arrival and $\pm$ .01 μsec. for the 11 arrival. The relative accuracy of a series of readings in a pressure sequence is greater than the accuracy of a single measurement. This relative error usually is about $\pm$ .02 μsec. Tables 3, 4, and 5 present the velocties and selected important elastic moduli for pressure-temperature combinations corresponding very roughly to depths within the crust. Table 3 at 30°C, 35 kg/cm^2 corresponds to 100 m.; Table 4 at 100°C, 527 kg/cm^2 to 2000 m.; Table 5 at 150°C, 1055 kg/cm^2 to 4000 m.

Figure 3 compares for the different rocks the dilatational velocities as a function of pressure at 30°C; Figure 4 compares the rotational velocities under the same conditions. Figure 5 shows the variation of V_D with both pressure and temperature for a specific rock—quartz monzonite—, and Figure 6 presents this material for V_R. Figures 7 and 8 compare V_D and V_R for enclosed and unenclosed samples of particular rocks.

Clearly, it was not feasible to present tables and graphs for all the moduli as functions of pressure and temperature. Indeed, the accuracy of the method probably does not justify such a detailed presentation. However, from the data presented a complete set of figures and tables could be prepared if desired.

Discussion of Results

Although the work described here is of a preliminary nature, much information may be derived from it. The difference in behavior of enclosed and unenclosed samples is striking. The former show rather large velocity changes at the lower pressures; the rate of change becomes much less at higher pressures. The open

TABLE 1.—DILATATIONAL VELOCITIES OF IGNEOUS ROCKS IN M/SEC.

Rock Type	Temp. °C	Pressure in kg/cm²						
		35	176	352	527	703	879	1055
Granite	30°	5519	5798	5999	6109	6163	6205	6232
	100°	—	5606	5801	6052	6081	6127	6183
	154°	—	5319	5515	5667	5863	5974	6077
Andesite	32°	5230	5244	5255	5266	5281	5284	5310
	107°	5133	5176	5208	5226	5230	5251	5273
	158°	5119	5154	5186	5208	5230	5233	5251
Quartz Monzonite	30°	5259	5621	5818	5900	5946	5976	5998
	101°	4830	5293	5675	5818	5892	5955	5981
	150°	4484	4959	5341	5591	5746	5830	5892
Diorite	33°	5783	5970	6114	6196	6243	6275	6301
	102°	5434	5733	5980	6088	6170	6196	6232
	151°	5271	5590	5913	6014	6093	6170	6196
Norite	32°	6181	6495	6649	6758	6811	6851	6877
	100°	5860	6303	6550	6675	6771	6824	6851
	152°	—	6143	6483	6656	6745	6811	6831

TABLE 2.—ROTATIONAL VELOCITIES OF IGNEOUS ROCKS IN M/SEC.

Rock Type	Temp. °C	Pressure in kg/cm²						
		35	176	352	527	703	879	1055
Granite	30°	3043	3234	3301	3398	3426	3454	3474
	100°	—	3187	3232	3320	3325	3314	3327
Andesite	32°	2734	2784	2815	2832	2840	2846	2844
	107°	2698	2734	2776	2800	2811	2814	2825
	158°	2629	2718	2753	2764	2783	2808	2818
Quartz Monzonite	30°	2894	3091	3146	3196	3203	3212	3229
	101°	2811	2894	3107	3183	3202	3203	3226
	150°	2670	2862	2982	3106	3148	3178	3181
Diorite	33°	3056	3173	3254	3302	3310	3318	3322
	102°	2871	3090	3171	3246	3291	3299	3312
	151°	—	3017	3114	3186	3226	3262	3277
Norite	32°	3239	3377	3516	3575	3582	3606	3632
	100°	2916	3243	3392	3507	3546	3550	3558
	152°	—	3231	3306	3435	—	—	3529

TABLE 3.—ELASTIC MODULI OF IGNEOUS ROCKS AT 30°C, 35.15 KG/CM²

Rock Type	Sample	V_D	V_R	$k \times 10^{11}$	$\mu \times 10^{11}$	σ	ρ
		m/sec.	m/sec.	dynes/cm²	dynes/cm²		gm/cm³
Granite	Enclosed	5519	3043	4.71	2.41	.282	2.601
	Open	5811	3366	4.94	2.95	.248	
Andesite	Enclosed	5230	2734	4.55	1.96	.312	2.618
	Open	5167	2787	4.28	2.03	.295	
Quartz Monzonite	Enclosed	5259	2894	4.33	2.20	.283	2.628
	Open	5958	3428	5.21	3.09	.253	
Diorite	Enclosed	5783	3056	6.46	2.83	.306	3.026
	Open	6058	3408	6.42	3.51	.269	
Norite	Enclosed	6181	3239	7.24	3.21	.307	3.057
	Open	6693	3561	8.52	3.88	.302	

TABLE 4.—ELASTIC MODULI OF IGNEOUS ROCKS AT 100°C, 527.3 KG/CM²

Rock Type	Sample	V_D	V_R	$k \times 10^{11}$	$\mu \times 10^{11}$	σ
		m/sec.	m/sec.	dynes/cm²	dynes/cm²	
Granite	Enclosed	6052	3320	5.70	2.87	.285
	Open	5768	3328	4.81	2.88	.250
Andesite	Enclosed	5226	2800	4.22	2.05	.299
	Open	5190	2770	4.37	2.01	.301
Quartz Monzonite	Enclosed	5818	3183	5.35	2.66	.287
	Open	6019	3459	5.16	3.03	.254
Diorite	Enclosed	6088	3246	6.97	3.19	.302
	Open	6161	3457	6.66	3.62	.270
Norite	Enclosed	6675	3507	8.60	3.76	.309
	Open	6841	3514	9.26	3.77	.321

TABLE 5.—ELASTIC MODULI OF IGNEOUS ROCKS AT 150°C, 1055 KG/CM²

Rock Type	Sample	V_D	V_R	$k \times 10^{11}$	$\mu \times 10^{11}$	σ
		m/sec.	m/sec.	dynes/cm²	dynes/cm²	
Granite	Enclosed	6077	—	—	—	—
	Open	5622	3193	4.69	2.65	.262
Andesite	Enclosed	5251	2818	4.43	2.08	.297
	Open	5213	—	—	—	—
Quartz Monzonite	Enclosed	5892	3181	5.58	2.66	.294
	Open	5773	3293	4.96	2.85	.259
Diorite	Enclosed	6196	3277	7.29	3.25	.306
	Open	6200	3451	6.83	3.60	.276
Norite	Enclosed	6831	3529	9.19	3.81	.318
	Open	6772	3496	9.04	3.74	.318

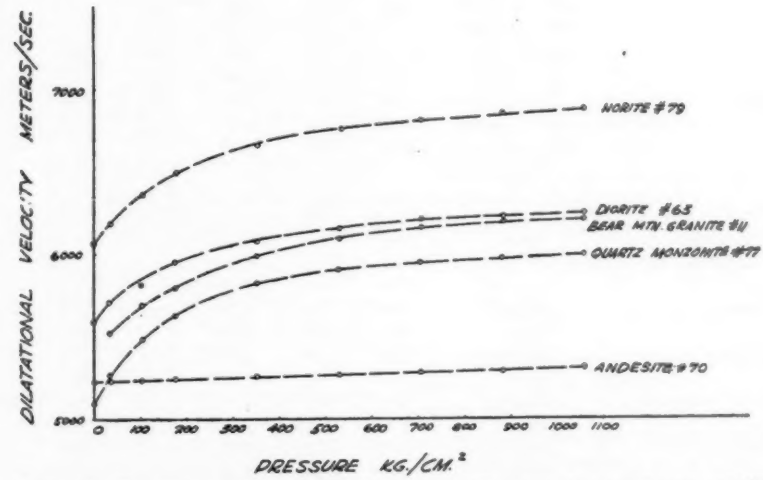

FIGURE 3.—DILATATIONAL VELOCITY VS. PRESSURE OF ENCLOSED IGNEOUS ROCKS AT 30°C

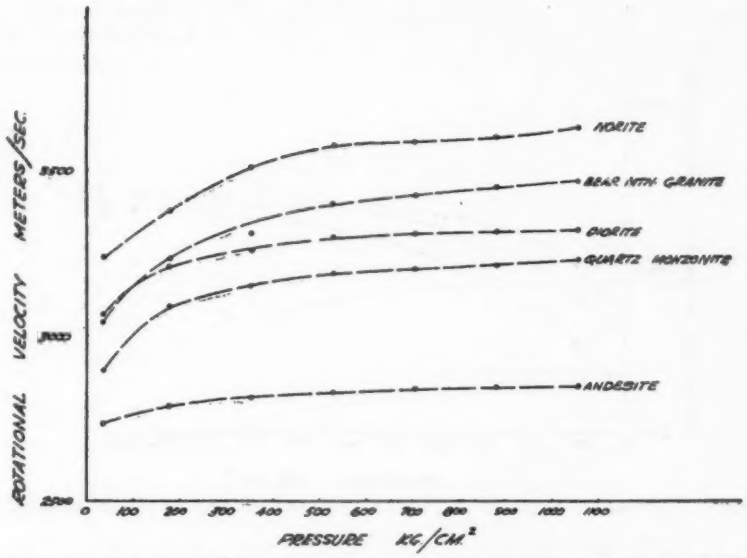

FIGURE 4.—ROTATIONAL VELOCITY VS. PRESSURE OF ENCLOSED IGNEOUS ROCKS AT 30°C

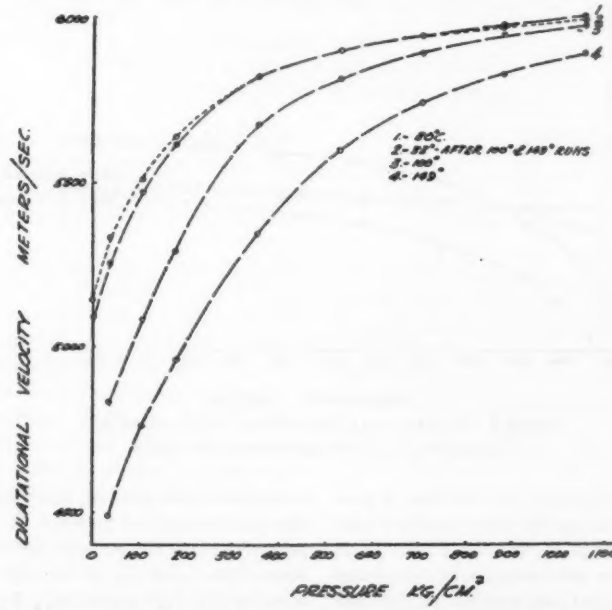

FIGURE 5.—DILATATIONAL VELOCITY VS. PRESSURE AND TEMPERATURE OF QUARTZ MONZONITE

samples vary but slightly and almost linearly over the pressure range. This difference may be explained by postulating the existence of pore space in the rocks. Presumably these spaces

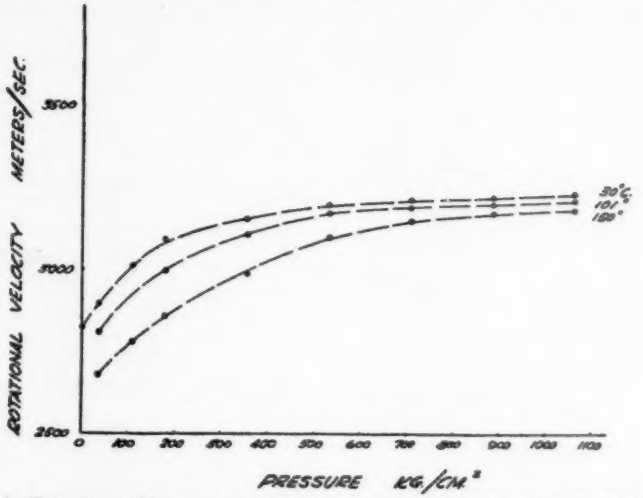

FIGURE 6.—ROTATIONAL VELOCITY VS. PRESSURE AND TEMPERATURE OF QUARTZ MONZONITE

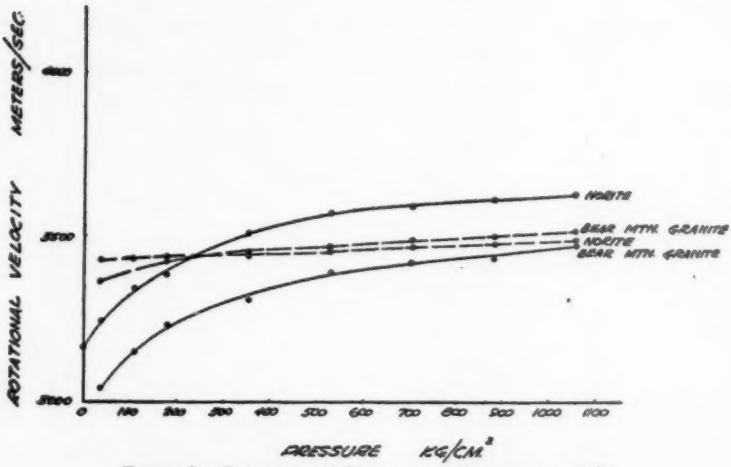

FIGURE 7.—DILATATIONAL VELOCITY VS. PRESSURE AT 30°C
Comparison of enclosed and unenclosed samples.

are originally occupied by air. Increase of pressure rapidly closes up the pores causing a relatively great change in velocity at the lower pressures. In the open samples, oil penetrates the void spaces and puts pressure on the individual grains of the rock. The compressibility of the oil (SAE 10) is, of course, much less than that of air, and its acoustic velocity is several times greater. Accordingly, the velocities in the unenclosed specimens are much higher than in the enclosed at low pressure. If all the pore space is closed, the enclosed specimens should show higher velocities at the highest pressures than do their open equivalents. An intersection of V_D vs. p curves is actually observed in the granite. In the other phaneritic rocks, however, the unenclosed dilatational velocities at the highest pressures are still slightly higher than

in the enclosed samples. This would indicate that at these pressures all the pore space has not been closed up.

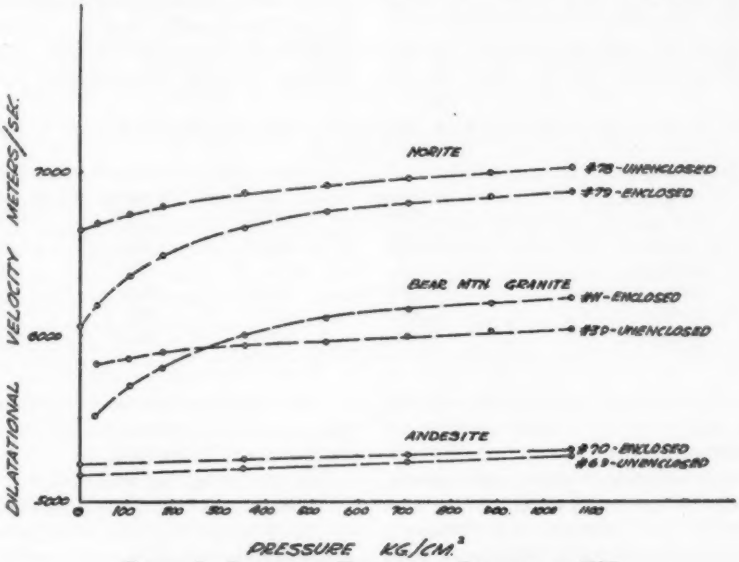

FIGURE 8.—ROTATIONAL VELOCITY VS. PRESSURE AT 30°C
Comparison of enclosed and unenclosed samples.

The rotational velocities are somewhat higher for the unenclosed specimens for diorite, Bear Mountain granite, and quartz monzonite, whereas in the norite and andesite the curves intersect.

In general for any given pressure and temperature, the enclosed sample shows a higher value of μ and lower values of k and σ than the unenclosed sample. The quantities k and μ show an increase with rising pressure and a decrease with rising temperature. Values of σ fluctuate somewhat erratically, but the trend suggests a slight increase at higher pressures. Data is insufficient to warrant generalizations as to the variation of σ with temperature. Tables 3, 4, and 5 indicate a steady increase of k and μ with depth for enclosed specimens; the change of σ again is erratic. The open samples are more variable; some even indicate a decrease in the values of k and μ with increasing depth.

We can make some crude calculations indicative of the porosity effect. If we consider the dilatational wave through a specimen, both open and jacketed, at room temperature and pressure, we may write two equations:

$$t_1 = \frac{L - l}{V} + \frac{l}{V_a} \tag{8}$$

$$t_2 = \frac{L - l}{V} + \frac{l}{V_o}, \tag{9}$$

where t_1 and t_2 are observed travel times, L the length of the sample, l the total length traveled through pore space, V the true rock velocity, V_a the velocity in air, and V_o the velocity in the oil. If we define a "linear porosity" $l/L = q$, we may rewrite the above expressions:

$$1/V_1 = t_1/L = \frac{1 - q}{V} + q/V_a \tag{10}$$

$$1/V_2 = t_2/L = \frac{1 - q}{V} + q/V_o. \tag{11}$$

V_a, V_1, and V_2 are known, and V_o is easily measured and found to be 1425 m/sec. at 30°C and atmospheric pressure. Thus we have two equations in two unknown, V and q. If we solve these, we obtain the following explicit expressions for V and q:

$$q = \frac{V_0 V_a}{V_1 V_2} \frac{(V_2 - V_1)}{(V_0 - V_a)} \tag{12}$$

$$V = \frac{V_1 V_a (1 - q)}{(V_a - qV_1)} = \frac{V_2 V_0 (1 - q)}{(V_0 - qV_2)}. \tag{13}$$

To obtain an approximate check, we may compare the values thus obtained with the values of V obtained by projecting the flat portion of the V_D vs. $\dot{p}$ curves back to the $\dot{p} = 0$ axis (Table 6).

TABLE 6.—COMPARISON OF CALCULATED AND MEASURED VALUES OF POROSITY AND TRUE DILATATIONAL ROCK VELOCITY

Rock Type	Calculated porosity	Calculated true rock velocity	Measured porosity	Graphical true rock velocity
Granite	.0070	5931	.0011	6050
Andesite	—	—	.0011	5200
Quartz Monzonite	.0120	6175	.0014	6300
Diorite	.0057	6143	.0021	6150
Norite	.0063	6724	.0019	6800

We may also obtain some rough porosity measurements by careful weighing of the sample before and after exposure to the oil. Porosity values thus obtained are of the order of a few tenths of a per cent. In general a sample kept at high pressure for a long period—*e.g.*, 24 hours at 10,000 p.s.i.—would approach equilibrium for that particular temperature. Increase of temperature caused some slight further penetration. Doubtless, complete penetration was never attained.

Hysteresis effects from heating to 100°C were slight or absent. (*See* Ide, 1937.) However, rocks heated to 150°C showed a slight gain in velocity over the entire pressure range when remeasured at room temperature, presumably owing to a consolidation of the material by closing of some of the void space. Similar "improvement" of rocks heated under high confining pressures was observed by Birch and Bancroft (1938), who inferred a tendency of rocks to return to the internal stress state which they had *in situ*. Ide found that at atmospheric pressure rocks heated to 200°C and beyond exhibited, upon cooling, large permanent decreases in velocity. Each heating to successively higher temperatures produced further irreversible acoustic wave-velocity decreases. Ide postulated that heating caused unequal expansion of the various crystal components of the rock resulting in the formation of cracks. Apparently the hydrostatic confining pressures utilized in the present work prevented the formation of such cracks, since in only the Salem diorite did heating to 150°C produce permanent decreases of elastic wave velocities. Evidently at the temperature-pressure conditions attained, these two agencies combine to effect a slight decrease in pore space.

The only fine-grained rock studied, andesite, showed but slight variation in velocity throughout the pressure range. Also the open and enclosed samples differed by an amount within the experimental accuracy limits. Presumably this behavior may indicate less connected void space. The large amount of glassy material—about 20–40 per cent—probably accounts for the low wave velocities and low density observed for this rock.

Ide (1937) found that certain glasses, including Pyrex, silica glass, and natural obsidian, showed a definite increase in acoustic velocity with increase of temperature. Thus a rock containing both hyaline and crystalline material might be expected to show less decrease of wave velocity with increase of temperature than a wholly crystalline rock of similar composition. Observations of the Chaffee County, Colorado, andesite confirm this.

In general, the velocities increase with rising pressure and decrease with rising temperature. As we go down within the earth these two agencies oppose one another. Evidently at the depths simulated by our experimental conditions the two variables interact to produce a gradual increase in wave velocities, and the rate of increase decreases downward.

Comparison with the work of other investi-

gators (Adams and Williamson, 1923; Birch and Bancroft, 1938; 1940; Birch *et al.*, 1942) suggests that the graphs of V_D and V_R vs. pressure are essentially straight lines at pressures beyond 1100 kg/cm². The present apparatus is being modified to permit measurements up to 3500 kg/cm² and possibly higher.

The advantage of the method of study described here is that one obtains both wave velocities in a single, simple operation and can therefrom compute all the elastic parameters. To take full advantage of the method, correct identification and precise, accurate timing of the various events are essential. The first, or dilatational, arrival retains its character throughout the pressure range, though it loses sharpness at higher temperatures and occasionally could not be read at high temperature and low pressures. It is sometimes difficult to identify 11, the once-delayed arrival. The latter often breaks up into several events, probably owing to the creation of new high velocity paths by closing up of pore space. Also, at high temperatures, this event loses much of its sharpness and is reduced in amplitude, and occasionally could not be read with precision. The confining jacket also appears to reduce the sharpness and amplitude of this event.

It is believed that the results obtained compare favorably in accuracy and precision with the work of other investigators. Since the materials investigated differ from those studied by other workers, agreement should not be expected to be exact.

Adams and Williamson (1923) measured the compressibility of a large number of rocks and minerals using a piston-bomb apparatus. By assuming a value of 0.27 for σ they were able to calculate the other elastic moduli and the elastic wave velocities. Zisman's (1933) measurements, like those of Adams and Williamson, were static. He employed a lever-piezometer and a rocking-mirror strain apparatus to make independent measurements of E, σ, and the compressibility. Zisman made a comparison of various static laboratory measurements with values of the elastic moduli calculated from seismic field observations and found that the latter were consistently higher.

In addition to these static methods, dynamical methods have been used to study the elasticity of rocks (Siegel, 1944). In general these require determination of the resonant frequencies of vibration of samples of simple geometrical shape. The most important contributions are those of Ide (1937), who measured longitudinal resonant frequencies of cylinders, and Birch and Bancroft (1938; 1940), who measured torsional vibrations in cylinders. Agreement of present measurements obtained at effective frequencies of 2–6 megacycles with the low frequency seismic values of Leet (1933) and the work of Birch and Bancroft at a few kilocycles suggest that for rocks the effect of frequency on velocity is negligible. More data are needed, however, before this can be asserted with any certainty. Studies of the effect of possible dispersion are being carried out at present and their discussion in a later paper is contemplated.

To be of further interest for igneous rocks, the pressure and temperature range must be extended. Experiments within the present range should yield valuable information on sedimentary rocks, and investigations of these materials have been initiated. The results certainly indicate the order of magnitude of elastic wave velocities and elastic parameters and their variation with pressure from 500 to 15000 p.s.i. To establish definitely the variations with temperature, observations at several more temperatures will be required. Attempts to make inferences regarding the earth's interior have been postponed until data at higher pressures can be obtained and until measurements of ultrabasics have been completed. It is also hoped that specific materials studied by previous investigators may be examined by this method.

References Cited

Adams, L. and Williamson, E. (1923) *On the compressibility of minerals and rocks at high pressures*, Franklin Inst., Jour., vol. 195, p. 475-529.

Barnes, V., Dawson, R., and Parkinson, G. (1942) *Building stones of central Texas*, Bur. Econ. Geol., U. Texas Pub. 4246, p. 58-60.

Birch, Francis (1943) *Elasticity of igneous rocks at high temperatures and pressures*, Geol. Soc. Am., Bull., vol. 54, p. 263–286.

——and Bancroft, D. (1938) *The effect of pressures on the rigidity of rocks*, Jour. Geol., vol. 46, p. 59–87, p. 113–141.

—— —— —— (1940) *New measurements of the rigidity*

of rocks at high pressure, Jour. Geol., vol. 48, p. 752–766.

——, Schairer, J. F., and Spicer, H. C. (Editors) (1941) *Handbook of physical constants*, Geol. Soc. Am., Special Papers, No. 36.

Clark, R. W. (1916) *Descriptive catalogue of a petrographic collection of American books*, Ward's Nat. Sci. Est.

Dale, T. N. (1908) *The chief commercial granites of Massachusetts, New Hampshire, and Rhode Island*, U. S. Geol. Survey, Bull. 354, p. 188.

Grammel, R. M. (1928) *Mechanik der elastischen Korper*, Handbuch der Physik, B. VI, Springer, Berlin, p. 323–324.

Hughes, D. S., Blankenship, E. B., and Mims, R. L. (1950) *Variation of elastic wave moduli with pressure and temperature in plastics*, Jour. Applied Physics, April.

——, Pondrom, W. L., and Mims, R. L. (1949) *Transmission of elastic pulses in metal rods*, Phys. Rev., vol. 75, p. 1552–1556.

Ide, J. M. (1937) *The velocity of sound in rocks and glasses as a function of temperature*, Jour. Geol., vol. 45, p. 689–716.

Kemp, J., and Ruedemann, R. (1910) *Geology of the Elizabethtown and Port Huron quadrangles*, N. Y. State Mus., Bull. 138, p. 52–57.

Leet, L. D. (1933) *Velocity of elastic waves in granite and norite*, Physics, vol. 4, p. 375–385.

NDRC (1946) *Supersonic solid delay lines*, Div. 14, OEMsr-262, Report 932.

Siegel, S. (1944) *A review of supersonic methods for measuring elastic and dissipative properties of solids*, Jour. Acous. Soc., vol. 16.

Washington, H. S. (1917) *Chemical analysis of igneous rocks*, U. S. Geol. Survey, Prof. Paper 99, p. 607.

Zisman, W. A. (1933) *Young's modulus and Poisson's ratio with reference to geophysical applications*, p. 653–665; *Compressibility and anisotrophy of rocks at or near the earth's surface*, p. 666–680; *A comparison of the statically and seismologically determined elastic constants of rocks*, p. 680–686, Nat. Acad. Sci., Pr., vol. 19.

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Manuscript Received by the Secretary of the Society, December 9, 1949

MAP OF CENTRAL APPALACH

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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SOME EFFECTS OF DEFORMATION IN THE CENTRAL APPALACHIANS

By Jacob E. Gair

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Abstract

Deformation in the folded Cambrian to Devonian sedimentary rocks of the central Appalachians has been investigated, mainly in the Potomac River Valley. Interpretations of deforming mechanisms are based on the study of folds, rock cleavages, faults, and lineations. An attempt is made to present a kinematic analysis of deformation. Effects of deforming movements, such as preferred orientations, cleavages, small-scale thrusts, and alterations of primary stratigraphic thicknesses are analyzed and correlated.

Changes in deformation are related to (1) differences in location within the folded Appalachian belt; (2) different stratigraphic horizons; (3) different positions in given folds; (4) lithological differences.

It has been found that:

1. Deformation decreases westward from the South Mountain-Blue Ridge belt. This corroborates the previous findings of Cloos and Fellows;

2. Less competent limestones are deformed farther toward the west than the more competent sandstones. Each formation of differing relative competency has its own tectonite front, and thus, for the succession as a whole, there is a series of tectonite fronts approximately parallel to the western edge of the Appalachian Valley;

3. Distortion of primary thicknesses are correlated with cleavage-bedding angles in separate beds of a given fold in which transverse cleavage is prominent;

4. Changes in thickness corresponding to changes in cleavage-bedding angles occur in the less compe-

tent rocks west of the Appalachian Valley; they are inferred for the rocks in the Valley;

5. Radical changes in thickness often have been caused by bedding-plane slip, interleafing, and piling-up of shales between more competent layers;

6. Bedding-plane thrusts cause repetition of individual layers;

7. Bedding-plane slip and thrusting parallel to bedding are the predominant modes of distortion west of the Appalachian Valley.

Acknowledgments

This study progressed under the guidance of Ernst Cloos. Many helpful suggestions were made by the other faculty members of the Department of Geology of The Johns Hopkins University. The writer was assisted in the field by his wife, Peggy Lou Gair.

Introduction

This is a study of the deformation of quartzites, sandstones, shales, and limestones in the central Appalachians. The field and laboratory work was carried on during 1947, 1948, and early in 1949. Structures in lower Cambrian to upper Devonian rocks, and statistical fabric diagrams, have been used to interpret deformative mechanisms. A comparison of data indicates regional changes in deformation.

The following report is offered as: (1) an analysis of kinematics in the folded sedimentary rocks of the central Appalachians; and (2) a study of the effects produced by deformation, such as the development of cleavages, small-scale thrusts, and changes in primary stratigraphic thicknesses.

The Area

The central Appalachian region consists of four physiographic belts traversed by the Potomac River (Pl. 1; Table 1).[1]

Blue Ridge-South Mountain Uplift: The South Mountain anticline contains lower Cambrian or pre-Cambrian metavolcanics overlain by lower Cambrian phyllites and quartzites (Cloos, 1941). The rocks are intensely cleaved and deformed. Quartz grains in the Weverton are elongated to more than double their thickness. The anticline is overturned toward the northwest and the axial plane dips about 30° southeast.

Appalachian or Great Valley: This broad valley is underlain principally by limestones and dolomites which extend stratigraphically from the Tomstown dolomite to the Chambersburg limestone. The youngest formation in the Valley is the Martinsburg shale. The tight folds of the Valley are overturned progressively less toward the northwest. In the vicinity of Hagerstown, Maryland, axial plane dips have increased to 70–80° southeast. Oölites (Cloos, 1947), calcite grains, and mud lumps show progressively less elongation toward the northwest. Near the western border of the Valley, axial planes are essentially vertical, indicating an approach to symmetrical folding.

Folded Appalachian Ridges and Valleys: The rocks in the area are Silurian, Devonian and lower Mississippian. The Tuscarora and Keefer sandstones occur in bordering anticlinal and synclinal ridges in the eastern part of the belt. Devonian rocks skirt the ridges and occupy the intervening valleys. Near Hancock, Maryland, middle and upper Silurian rocks occur in the core of an anticline. The overlying Oriskany sandstone forms Tonoloway and Cove ridges on the limbs of the anticline. Sideling Hill, 5 miles west of Hancock, is a large syncline with Mississippian rocks in the trough. Westward from Sideling Hill, the major ridges are formed on anticlines or synclines. The broadest folds are in Devonian and lower Silurian rocks. The upper Silurian thin limestones and shales are the most complexly folded rocks cropping out in the central Appalachians.

Allegheny Plateau: A few miles west of Cumberland, Maryland, the folds die out; Silurian and Devonian rocks dip gently beneath the Plateau, and evidences of appreciable deformation disappear.

Historical Note

The northeast trend of the parallel folds in the Appalachians, and the southeasterly dips of strata and axial planes in the Appalachian Valley and Blue Ridge were early recognized by W. B. Rogers and H. D. Rogers (1843).

[1] For details see geologic maps of Washington County, Maryland (Cloos, 1941), and Allegany County, Maryland (Clark, 1900), and U. S. Geological Survey Folio 179 (Stose and Swartz, 1912).

TABLE 1.—LOWER AND MIDDLE PALEOZOIC FORMATIONS IN CENTRAL APPALACHIANS OF MARYLAND
(Slightly modified from Geologic Map of Washington County)

System	Formation	Description
Devonian	Catskill formation	Red, micaceous sandstone and shale with green, yellow, and grayish, sandy layers
	Jennings formation	Platy, gray shale and buff, sandy shale with thin conglomerate beds and Parkhead sandstone member
	Romney shale	Dark-gray to black, sandy, fissile to hackly shale with several sandstone layers in upper part
	Oriskany sandstone	White, quartzose sandstone; gray, sandy, and cherty limestone; fine quartz conglomerate
	Helderberg limestone	Massive, dark-blue limestone and shaly, cherty limestone
Silurian	Tonoloway limestone	Finely laminated, drab to dark-gray limestone, weathering to shaly limestone
	Wills Creek shale	Platy, drab, calcareous shale; shaly limestone, and locally hard, white sandstone. Bloomsburg red sandstone member at base
	McKenzie formation	Gray shale with crystalline and laminated limestones
	Clinton shale	Drab to pink, fine shale and thin sandstone; Keefer white, hard sandstone member at top
	Tuscarora sandstone	Hard, white, massive and thin-bedded quartzose sandstone
Ordovician	Juniata formation	Soft, red sandstone and shale with local quartz conglomerate
	Martinsburg shale	Soft, buff to black, sandy shale
	Chambersburg limestone	Rather pure, thin-bedded limestone with argillaceous partings
	Stones River limestone	Very pure, even-grained limestone with some magnesian beds
	Beekmantown limestone	Light-gray, magnesian limestone and shaly, cherty limestone
Cambrian	Concocheague limestone	Hard, siliceous, banded limestone and calcareous sandstone with limestone pebbles
	Elbrook limestone	Thinly laminated, fine-grained, argillaceous limestone; weathers to buff, earthy limestone
	Waynesboro formation	Red shales and sandstone with some interbedded limestone
	Tomstown dolomite	Principally dark, knotty dolomite; interbedded, blue-banded limestone and shale in upper part
	Antietam quartzite	Gray to buff, ferruginous quartzite
	Harpers phyllite	Gray phyllite and slate, purple, banded with quartzose phyllite and calcareous layers
	Weverton quartzite	Light-gray to dark, purple, banded, granular to vitreous quartzite; white quartzite in upper part
	Loudon formation	Highly ferruginous, dark, sandy phyllite; thin and thick-bedded, arkosic, pebbly quartzite

ROCK COMPETENCY, FLOW, AND FRACTURE: Bailey Willis (1893) concluded that differences in competency depend essentially on differences in viscosity or cohesion, which in turn determine whether a rock will flow or fracture during deformation. Heim (1878) and Van Hise (1896)

related deformation by fracture or flow to the depth of burial of the rock during deformation, and Van Hise postulated the existence of definite zones of flow and fracture for rocks of differing competency. This concept includes the idea of "a zone of combined fracture and flowage" where rocks of differing competency occur alternately.

COMPONENTAL MOVEMENTS: The distinctions between rupture and solid flow (or plastic deformation), and between solid flow in rocks and in crystals should be clearly drawn:

> ". . . the one . . . *solid flow* in the widest meaning of the term, in which the continuity of the rock is retained despite the movements; the other . . . *rupture*, in which the continuity is destroyed. Solid flow embraces Sander's *componental movement* . . . defined by him as follows . . . 'As componental movement we name each movement of any element in a rock, as a result of which, after the deformation, and for the time under consideration, the rock retains its continuity.' " (Fairbairn, 1942, p. 5–6).

The differential componental movements of solid flow may also include the intragranular solid flow of crystals in which parts of the lattice are displaced by twin gliding or translation gliding without destroying the physical continuity of the individual grains.

A less generalized and qualitative approach to the study of rock behavior has led to interpretations of actual deforming mechanisms by Becker (1893), Sander (1911; 1930), Schmidt (1927; 1932), and many others. This work has been discussed by Knopf (Knopf and Ingerson, 1938, Pt. I), by Fairbairn (1942), and by Turner (1948).

The fundamental problem is the determination of the type of componental movement. The study of direct componental movements and their relationships to the larger movements of folding leads to a kinematic analysis of deformation (Knopf and Ingerson, 1938, p. 122; Turner, 1948, p. 163), which emphasizes constructing a movement picture rather than relating movements to ultimate causes; hence, a detailed stress-strain analysis is not implied.

FIELD AND LABORATORY METHODS

General Field Procedure

The present investigation attempts to relate changes in deforming mechanisms and effects of deformation to four principal factors: (1) differences in location within the folded Appalachian belt; (2) relative differences in depth of burial as indicated by stratigraphic position; (3) differences of position in given folds; (4) lithological differences

The field work consisted of examining exposures along a traverse which generally followed the Potomac River Valley from the junction with the Shenandoah River at Harpers Ferry, West Virginia, to Keyser, West Virginia (Pl. 1).

Along much of its course the Potomac Valley if followed by the Baltimore and Ohio Railroad and the Western Maryland Railroad. There are many miles of fresh exposures in the long open cuts of the Western Maryland Railroad in particular. Cuts along the Western Maryland Railroad at Roundtop, Maryland, 3 miles southwest of Hancock, and across the Potomac from Great Cacapon, West Virginia, and along the Baltimore and Ohio Railroad at Pinto, Maryland, provide excellent exposures of upper Silurian formations.

Between Harpers Ferry and Williamsport, Maryland, scattered localities with more favorable exposures were examined to the north of the Potomac River in the Appalachian Valley of Maryland. Between Little Orleans and Paw Paw, the Potomac Valley was followed only for short distances because the river meanders in a belt parallel to the regional strike between those two points. Outcrops were examined along highways approximately parallel to the river. Such exposures are located principally on U. S. Highway 40, between Hagerstown and Cumberland, on Maryland Highway 51, between Paw Paw and Cumberland, and on West Virginia Highway 9, between Berkeley Springs and a point a few miles south of Paw Paw. All major rock units in the geologic column for the central Appalachians, and all lithologic varieties common to the area, were observed. Most folds were seen in cross section.

Reconnaissance traverses of the folded Applachians were made at considerable distances to the north and south of the Potomac Valley to compare briefly exposures, rock types, and appearances of deformation with similar features along the main traverse. In Pennsylvania, highway cuts were observed for 5 or 6 miles up the Juniata River from Amity Hall and many cuts were examined along the Pennsylvania Turnpike between Blue Mountain Interchange

and Bedford Interchange. In Virginia and West Virginia, many cuts were examined cursorily along U. S. Highways 33, 50, and 250, between the western border of the Appalachian Valley and the Allegheny Plateau.

Detailed Field Procedure

Detailed field work consisted of describing and analyzing small folds, rock cleavages, fractures, small-scale faults, and lineations. Oriented rock samples were taken from selected formations and selected places in given folds. Careful note was made of differences in thickness in individual beds in the limbs and at the bends of folds that were well-exposed in cross section. About 275 measurements of thicknesses and associated cleavage-bedding angles were made in small folds and these establish the fact that displacements have taken place parallel to cleavage. In thin, fissile, or hackly shales without lineation, or in more competent nontectonites, such measurements may provide the only clue to local tectonic transport.

Cleavage-bedding angles in many folds were found to correspond to lithological variations.

Striations on slickensided bedding and fault planes were the most common lineations measured. Lineations parallel to fold axes were especially useful in the field as an aid in marking off on oriented samples the plane perpendicular to the fold axis approximately parallel to which plane nearly all saw cuts were later made. The attitudes of bedding and cleavage were recorded at locations from which oriented samples were taken.

Laboratory Procedure

The oriented samples were thin sectioned and examined carefully with a petrographic microscope. Any striking features such as microfolding, traces of slippage planes, and stretched or fragmented grains, were noted. Twenty-four thin sections were studied on the universal stage, and, from these, 29 petrofabric diagrams have been prepared.

Indicators of Deformation

Folds and Lineations

The word "fold" is here a descriptive, rather than a genetic, term. The sharpest genetic distinctions have been made between flexure folds and shear folds (Fairbairn, 1942, p. 82–86).

Flexure folds (Fig. 1) form by the mechanical bending of competent beds between which there

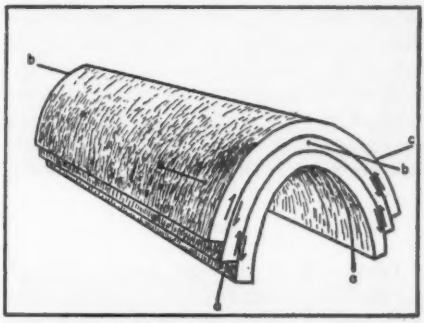


Figure 1. Flexure Fold

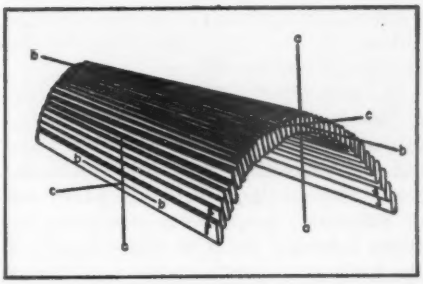


Figure 2. Shear Fold

may be less competent layers. The slipping of beds perpendicular to the axis of bending produces a relative displacement of the younger beds upward out of synclines. Shear folds (Fig. 2), on the other hand, form in relatively incompetent material (Cloos, 1947, p. 901), and ideally are the result of slipping transverse to bedding, sub-parallel to the axial plane, and perpendicular to the fold axis. This study shows that strata in central Appalachian folds commonly have been deformed by simultaneous displacements of material parallel with bedding in competent layers and transverse to bedding in incompetent layers. The effective movement in some beds may have been the resultant of tendencies toward such movements parallel with and transverse to bedding. The movements of flexure folding, however, appear to have been predominant west of the Appalachian

Valley. They were superseded to the east in the Valley and in the South Mountain fold by shear folding.

Lineations caused by elongation of oöids (Cloos, 1947), quartz grains (Fellows, 1943), or mud lumps (Pl. 2, fig. 1) transverse to bedding were not noted as megascopic features west of the middle of the Appalachian Valley. West of this part of the Valley, lineations were confined to bedding (slickenside striations; cleavage-bedding intersections; axes of microfolds) or to fault planes (slickenside striations).

Cleavage

Terms.—"Rock cleavage" here includes all closely spaced, secondary parting surfaces that form regular patterns in deformed rocks. Although the expression "closely spaced" is qualitative, it connotes to the writer a maximum spacing on the order of 1 centimeter. Cleavage surfaces are always irregular, but may be idealized as smooth surfaces.

The term "cleavage" is descriptive. The use of "flow cleavage" and "fracture cleavage" implies a knowledge of the mechanism of origin, but such distinctions often cannot be established. Theoretically, flow cleavage is the result of differential, homogeneous movements between individual grains or adjacent parts of the lattice in separate grains, and fracture cleavage results from systematic rupturing of a rock into segments made up of a number of grains. Some amount of shearing between the segments is implicit (Pl. 2, fig. 2). In practice, if the results of the componental movements of solid flow are visible in the fabric, or if they become apparent in fabric diagrams, an interpretation of "flow cleavage" is made (Pl. 2, figs. 3, 4; Pl. 4, D-1). When equidimensional quartz grains are embedded in a fine-grained, argillaceous matrix (Pl. 2, fig. 5; Pl. 4, D 22) they give no indication of componental movements, although such movements may have occurred, and no genetic interpretation of the cleavage can be made.

Cleavage patterns.—Cleavage patterns appear to be related to the type of movement involved in folding. The patterns shown in A and B of Figure 3 develop during flexure folding. They are found only west of the Appalachian Valley, in shale interbedded with limestone or sandstone. The bending and sliding of limestone layers contributed to the alignment of the clay minerals in the intervening shale in A (Fig. 3). The pattern shown in the shale in B (Fig. 3) is caused by the bending and slipping of limestone beds parallel to each other. At the arches of the folds, where limestone beds are forced apart, the cleavage bends outward into near parallelism with the axial plane. Often the limbs of the upper competent layer in an anticline are squeezed together slightly just below the crest because of a reduction in the amount of underlying support.

The sliding of competent beds during flexure folding is illustrated in E of Figure 3. The competent sandstone broke on the limb and then was thrust beyond the point of rupture into the core of the anticline.

Axial plane cleavage (Fig. 3, C) indicates ideal shear folding. It is common only in the formations of the extreme eastern part of the area, and in the Martinsburg shale in the west-central portions of the Appalachian Valley.

Fan cleavage in the South Mountain-Appalachian Valley region of Maryland has been mapped and described by Ernst Cloos (1941; 1947), who called the South Mountain anticline a shear fold in which the shear planes, or present cleavage surfaces, have spread upward and outward into a fan pattern. Cleavage in folds

PLATE 2.—ELONGATED ROCK COMPONENTS AND CLEAVAGE RIFTS

FIGURE 1. MUD LUMPS ELONGATED TRANSVERSE TO BEDDING
Conococheague limestone, 2 mi. S.W. of Clear Spring, Md.

FIGURE 2. DISPLACEMENT OF BEDDING ALONG WIDELY SPACED CLEAVAGE RIFTS
Wills Creek shale, 150′ W. of watchman's shack, Roundtop, Md.

FIGURE 3. STRETCHED QUARTZ GRAINS
Weverton quartzite, N. side of Potomac R. at Harpers Ferry, W. Va.

FIGURE 4. ELONGATED CALCITE GRAINS
Conococheague limestone, 4 mi. E. of Hagerstown, Md.

FIGURE 5. SCATTERED QUARTZ GRAINS IN CLEAVED, CALCAREOUS WILLS CREEK SHALE
Main anticline, Roundtop, Md.

FIGURE 6. RECRYSTALLIZED DOLOMITE GRAINS ASTRIDE RIFTS
Beekmantown limestone, 1 mi. S. of Clear Spring, Md.

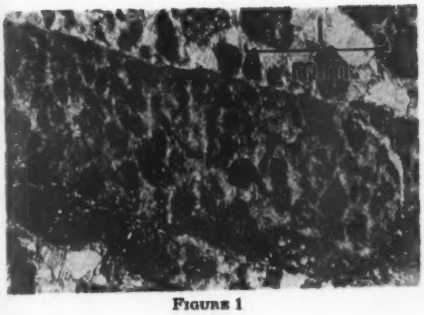


FIGURE 1

FIGURE 2

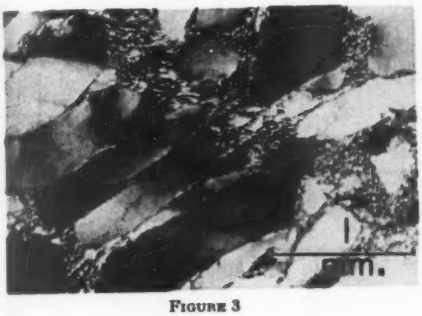


FIGURE 3

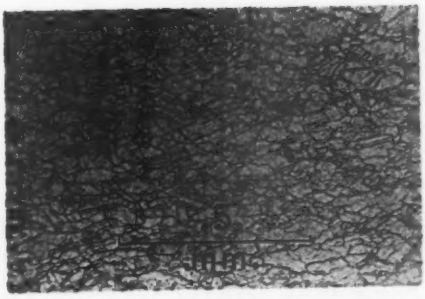


FIGURE 4

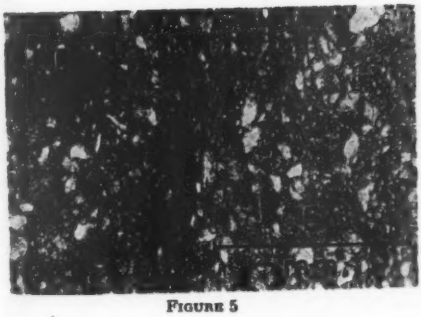


FIGURE 5

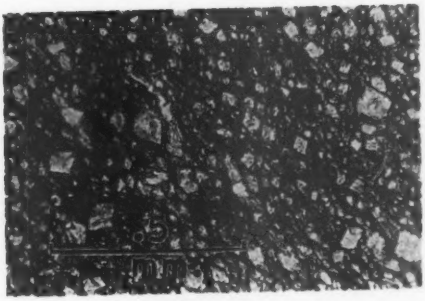


FIGURE 6

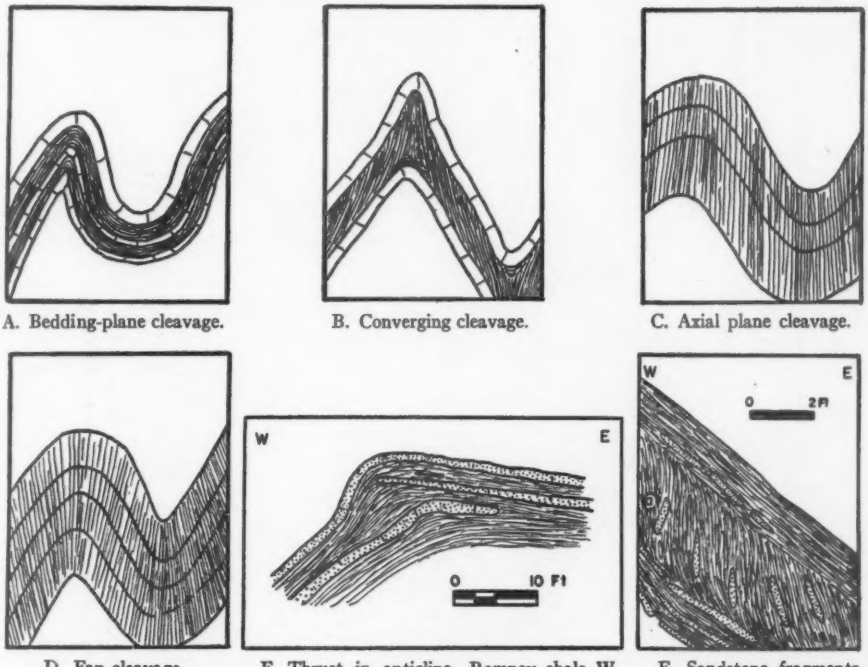
ELONGATED ROCK COMPONENTS AND CLEAVAGE RIFTS

of the Cambrian and Ordovician limestones in the Valley characteristically has a fan pattern (Fig. 3, D).

Fan cleavage is found west of the Appalachian Valley, notably in upper Silurian cal-

Petrofabric Diagrams

Preparation of diagrams.—The specimens collected range from lower Cambrian to middle Devonian (Table 2). Diagrams of quartz axes



A. Bedding-plane cleavage. B. Converging cleavage. C. Axial plane cleavage.

D. Fan cleavage. E. Thrust in anticline, Romney shale W. Md. R.R., *c.* 1 mi. E. of Spring Gap, Md. F. Sandstone fragments transverse to shale bed, Jennings formation, U. S. Highways 50 & 220. *c.* ¼ mi. W. of their conjunction.

FIGURE 3. FOLDS AND CLEAVAGE PATTERNS

careous and arenaceous shales, and in limestones. Variations in the thicknesses of beds in the prominent anticline in the Wills Creek shale at Roundtop, Maryland (Fig. 4) coincide with changes in the angles between fan cleavage and bedding. This indicates some displacement of material parallel to cleavage. The sigmoidal cleavage in the three lower beds of the anticline at Roundtop is a further illustration of the mechanism of bedding-plane slippage (Fig. 1). Local variations in the movement plan are shown by the cleavage patterns in Bed "a" of F (Pl. 3), and Bed "B" of Plate 3.

in quartzites, sandstones, shales, and impure limestones, and diagrams of *c* axes and poles of cleavage in calcite have been prepared (Pl. 4).

The petrofabric diagrams were prepared according to the standard method described by Ingerson (Knopf and Ingerson, 1938, Pt. II). All diagrams were counted out at half centimeter intervals to detect changes in the concentration of points more accurately. They are selective as to mineral, grain size, and mineralogical environment in the section. From place to place in a few sections these features are sufficiently different to have necessitated the preparation of more than one diagram.

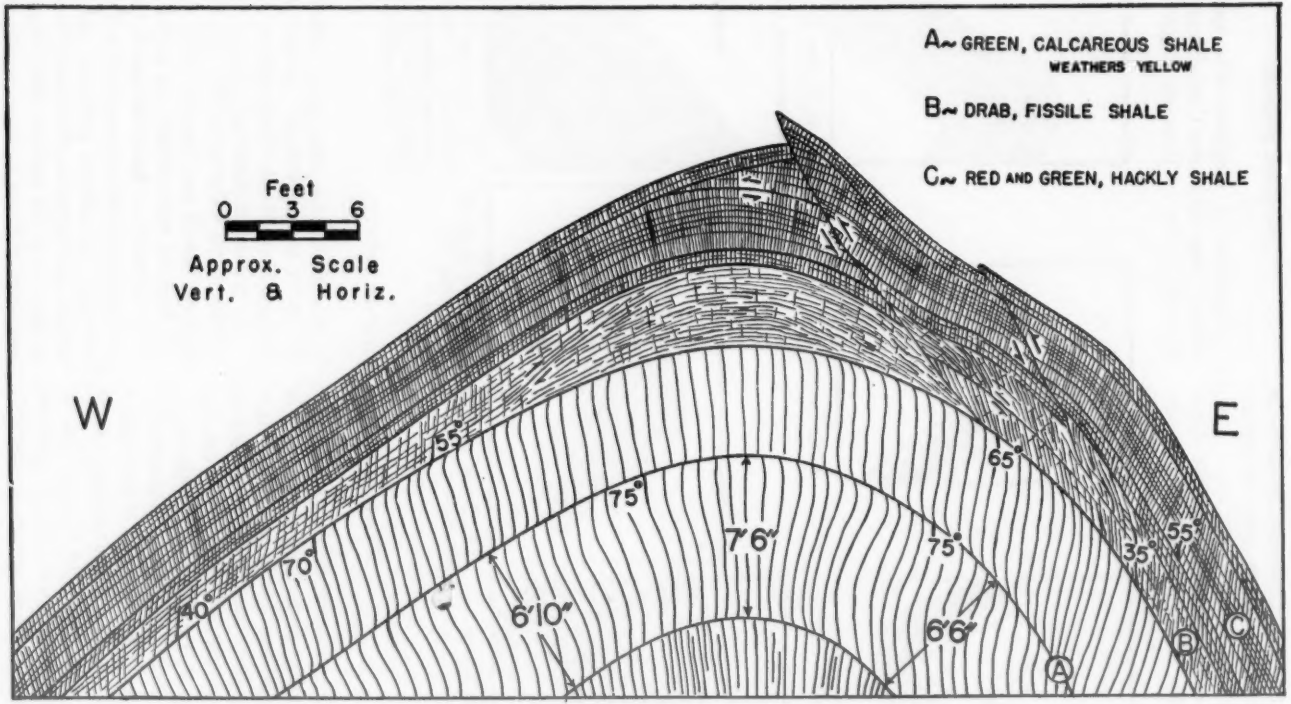
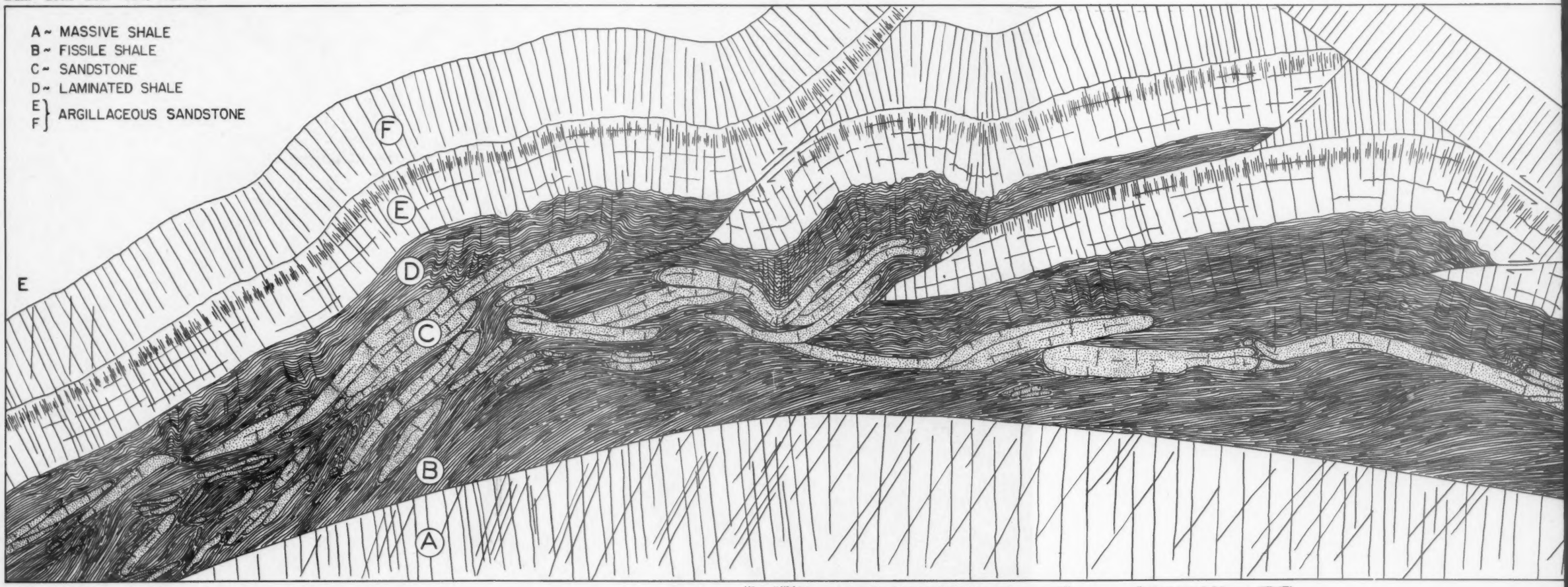
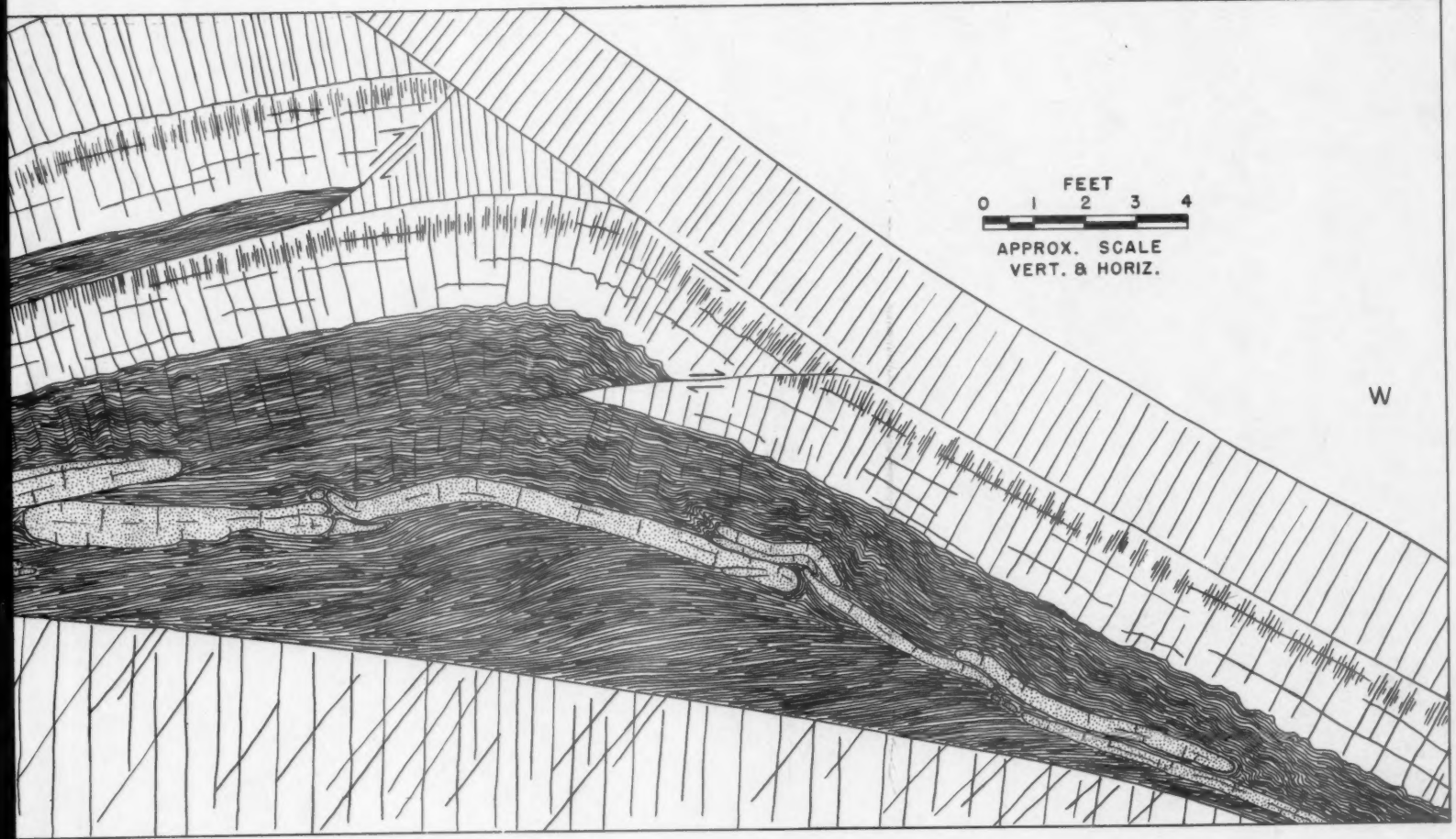


FIGURE 4. ANTICLINE AT ROUNDTOP, MARYLAND



MULTIPLE THRUSTS AT ROUNDTOP, MARYLAND



ROUNDTOP, MARYLAND

The Cloos system of orienting petrofabric diagrams is used (Cloos and Hietanen, 1941). All diagrams represent projections from the lower hemisphere (the hemisphere farthest from the observer) onto an equal-area net. The diagrams have been made as nearly as possible perpendicular to fold axes, without actually having rotated each point so as arbitrarily to bring fold axes to the exact center. The only diagram that was made parallel to the fold axis is D 3. The equatorial plane (equals net plane or plane of projection), therefore, is vertical or generally not more than 15–20° from the vertical, depending in part on the plunge of the fold axis.

The horizontal or strike line on the projection plane is shown by a long bar with an arrowhead at one end. The figure near the arrowhead indicates the value of the strike. All strikes can be shown by values between 0° and 180°. The strike arrow always points to the eastern half of the full azimuth circle or compass rose, (upper part, Fig. 5). Therefore, when a vertical diagram is placed at the center of the azimuth circle, and the observer is somewhere to the south of the diagram (S.E. or S.W. quadrants), the arrowhead will be to right of the observer (e.g., D 2a, D 5, D 8, Pl. 4). When the observer is to the north of the diagram (N.E. or N.W. quadrants), the arrowhead will be to his left (e.g., D 1, D 13, D 24, Pl. 4).

The dip of the surface of vertical or steeply inclined petrofabric diagrams is indicated by the short line attached at right angles to the strike line (Pl. 4). This line is always directed downward. The angle of dip, measured downward from the horizontal to the surface of the diagram, always opens toward the observer. The value for this angle is placed near the short dip line. If the diagram is vertical, the figure, 90°, near the short line indicates an angle that opens toward the observer and extends downward through an arc of 90°. The figure, 100°, indicates an angle extending downward through an arc of 100°. In this case, the surface of the diagram is overturned 10°, and the line of sight from the observer to the diagram must extend upward slightly. The lower part of Figure 5 illustrates the relationships between the position of the observer and the angle of dip.

The statistical fabric study has been restricted almost entirely to the area between South Mountain and Hancock, because that is the critical part of the traverse in which the tectonite zone passes into the zone of nontectonites.

Quartz diagrams.—The study of quartz-rich fabrics corroborates the findings of Fellows that granulation of grains is the predominant mode of accommodation to stress west of South Mountain. The positions of quartz maxima, however, do not conform to those of Fairbairn's synoptic diagram (1942, p. 68). On the basis of factors discussed by Fairbairn (1942, p. 70–71), translation gliding should be expected only in more highly deformed rocks. Although quartz grains in the eastern part of the area have strain shadows and undulatory extinction, the general absence of deformation lamellae (Hietanen, 1938, p. 31–40) seems to obviate translation gliding (plastic deformation of quartz) as the grain-orienting mechanism west of South Mountain.

Quartz orientation patterns become indistinct near the western border of the Appalachian Valley. The intensity of deformation of sandstone in the area is a function either of geographic or of stratigraphic position, or perhaps of both (Fellows, 1943, p. 1429). Across the Valley, between exposures of the Antietam quartzite and the Tuscarora sandstone, quartz diagrams (D 9, D 10, D 12) are derived from quartzose limestones. The deformation of the limestone was sufficient to produce quartz girdles, although the cushioning of quartz by calcite probably tended to retard development of preferred orientations. Consequently, orientation patterns for detrital quartz in limestone are no more pronounced than patterns for quartz in younger and less deformed sandstones cropping out west of the limestone. No continuous decrease in deformation intensity across the Valley is evident. Regional changes are best seen if orientations in the eastern part of the Valley are compared directly with those 20 to 30 miles to the west at the edge of the Valley and beyond.

Most diagrams from the Valley have complete *ac* girdles. Nearly complete girdles with maxima of 6 per cent are obtained from the Weverton quartzite (D 1) and quartzose layers in the Harpers phyllite (D 3). In the Tusca-

TABLE 2.—GRAIN DATA ON FORMATIONS FROM WHICH FABRIC DIAGRAMS WERE MADE

Formation	Diagram Number	Mineral	Local Characteristics of Mineral Grains	Typical Dimensions (mm.)	Grain Relations
Weverton quartzite	D 1	Quartz	Large, elongated, strained, or recrystallized	2.4x.6 1.8x.5 1.6x.5 .9x.2	Crush quartz between large, elongated quartz. Alignment of sericite produces strong fluxion structure around and at ends of elongated quartz grains.
			Crushed*	.015x.005 .005x.002	
		Sericite	Shred-like, flaky	.03x.003 .07x.003	
Harpers phyllite	D 2a D 2b D 2c D 2d D 3	Quartz	Large, elongated Medium, equant Small, equant	.8x.2 .1–.25 .03–.006	In places, fabric of medium quartz with minor amounts small quartz and sericite between medium quartz grains. Small crush quartz locally prominent along bedding planes. In other places, bulk of rock of small quartz, sericite, and chlorite. Transverse cleavage pronounced. Scattered calcareous layers contain large, elongated calcite and quartz grains.
		Calcite	Large, elongated	.8x.11 .65x.25	
		Sericite	Needle and shred-like	.015x.003	
		Chlorite	Flaky, lamellar	.015x.003 .03x.003	
Antietam sandstone	D 4	Quartz	Medium to small, equant Crushed, equant	.06–.13 .005–.01	Larger grains generally in contact with each other, with relatively little crush quartz between them.
Tomstown dolomite and limestone	D 5	Calcite and dolomite	Medium, equant Small, equant	.03–.06 .003–.006	Bulk of rock of smaller calcareous grains. Clusters of small grains recrystallize into larger grains. Largest grains few, and widely scattered.
		Calcite	Recrystallized, elongated	.06x.12 .25x.42	

Waynesboro sandstone	D 6	Quartz	Small, elongated Small, equant, strained Crushed (?)	.025x.065 .015–.045 .003	Rock mainly of small quartz. Bands of larger quartz in matrix of apparent crush quartz and sericite.
		Sericite	Elongated shreds	.0015x.006	
Elbrook limestone	D 7a D 7b	Calcite	Small, equant Medium, equant Medium, elongated	.0015–.006 .03–.4 .15x.4	Rock mainly of small calcite, clusters of which recrystallize to larger grains. Random large grains with twinning and cleavage.
Conococheague limestone	D 8 D 9 D 10 D 11	Calcite	Small, equant Medium, equant Medium, elongated	.01–.06 .06–.15 .02x.15	Rock mainly of small calcite with bands containing larger calcite and scattered detrital quartz. Parts of formation with elongated calcite (Pl. 2, fig. 4) occur just west of South Mountain.
		Quartz	Medium, equant	.06–.12	
Beekmantown limestone	D 12 D 13 D 14	Calcite and dolomite	Small, equant Small to medium, equant, recrystallized Small to medium, recrystallized within oölites Elongated oölites	.0015–.009 .02–.09 .78x.65 .65x.4	Rock mainly of small calcite with many larger recrystallized dolomite grains (Pl. 2, fig. 6) which developed along slip planes. Oölites in scattered layers.
		Quartz	Small, equant, detrital	.015–.8	
Chambersburg limestone	D 15	Calcite	Small, equant Small, elongated Medium to large, recrystallized	.001 .02x.06 .25–1.1	Rock mainly of small calcite. Scattered clusters of small grains recrystallize into larger grains
Tuscarora sandstone	D 16 D 17 D 18	Quartz	Medium to large, equant Small, equant, crushed	.1–1 .03–.06	Majority grains *c.* .3 mm. in diameter. Grains tightly packed and cemented. Minor amounts crushed quartz.

TABLE 2.—*Continued*

Formation	Diagram Number	Mineral	Local Characteristics of Mineral Grains	Typical Dimensions (mm.)	Grain Relations
Keefer sandstone	D 19 D 20 D 21	Quartz	Small to medium, equant Medium, equant Small, equant, crushed	.02–.15 .15–.25 .003–.006	Majority grains between .05 mm. and .15 mm. in diameter. Grains tightly packed. Minor amounts crushed quartz.
Wills Creek shale	D 22	Calcite and clay	Small, equant	.001–.004	Rock mainly of calcareous and argillaceous material. Random quartz averaging about .05 mm. in diameter.
		Quartz	Small, equant, detrital	.01–.08	
Oriskany sandstone (limestone member)	D 23a D 23b	Calcite	Small, equant Medium, equant Small and medium to large, lath-shaped	.01–.07 .1–.25 .06x.04 .15x.65	Bulk of rock consists of larger, equant calcite grains and large, intergrown, inequant, and randomly directed calcite. Relatively few small calcite between larger ones. Equant quartz grains scattered at random.
		Quartz	Medium, equant	.09–.25	
Romney shale (sandstone member)	D 24	Quartz	Small, equant	.002–.006 .015–.05	About half the rock consists smaller quartz grains and sericite scattered irregularly between larger quartz grains that make rest of rock.
		Sericite	Small, shredded	.0015x.006	

* See Fellows (1943).

VOYO

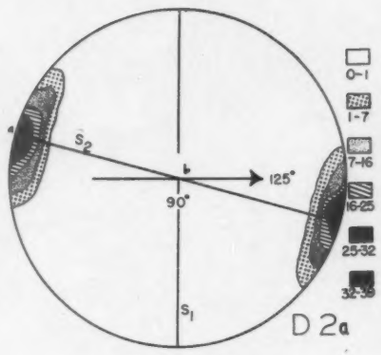
Explanation

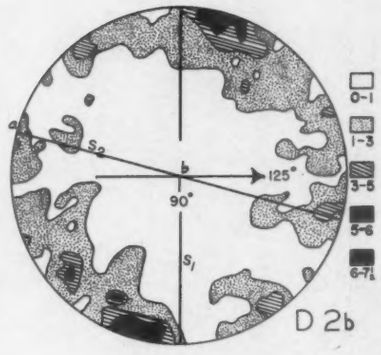
"D" for "diagram"
Small subscript letters after diagram numbers indicate more than one diagram prepared from same thin section
S1-----trace of bedding
S2-----trace of cleavage
a, b---standing alone indicate fabric axes
Contour intervals in per cent

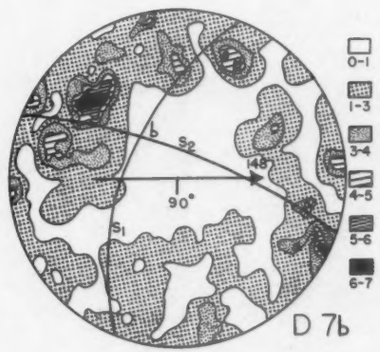
Diagram number	Number, type of grains, and elements measured	Rock type	Locality
D 1	200 large, strained, and elongated quartz (axes)	Cw	Harpers Ferry, W. Va.-Md.
D 2a	114 elongated calcite (dimensional orientations)	Ch	Harpers Ferry, W. Va.-Md.
D 2b	135 elongated calcite (poles of cleavage)	Ch	Harpers Ferry W. Va.-Md.
D 2c	125 small equant quartz in calcareous layer (axes)	Ch	Harpers Ferry W. Va.-Md.
D 2d	130 small equant quartz in phyllitic layer (axes)	Ch	Harpers Ferry W. Va.-Md.
D 3	200 medium quartz (axes)	Ch	4 mi. N. of Harpers Ferry, W. Va.
D 4	200 large and medium quartz (axes)	Ca	8 mi. N. of Harpers Ferry, W. Va.
D 5	100 medium and small calcite (axes)	Ct	1 mi. E. of Sharpsburg, Md.
D 6	200 medium quartz (axes)	Cwb	1 mi. E. of Sharpsburg, Md.
D 7a	100 calcite (poles of cleavage)	Ce	Three-fourths mi. E. of Sharpsburg, Md.
D 7b	100 calcite (axes)	Ce	Three-fourths mi. E. of Sharpsburg, Md.
D 8	150 small and medium calcite (poles of cleavage)	Ce	4 mi. E. of Hagerstown, Md.
D 9	200 quartz axes	Ce	3 mi. N. of Sharpsburg, Md.
D 10	200 quartz (axes)	Ce	Potomac R., 4¼ mi. N. W. of Sharpsburg, Md.
D 11	100 calcite (poles of cleavage)	Ce	2 mi. S. W. of Clear Spring, Md.
D 12	200 small quartz (axes)	Ob	One-half mi. N.E. Leitersburg, Md.
D 13	200 calcite (axes)	Ob	1 mi. S. of Clear Spring, Md.
D 14	200 calcite within deformed ooids (axes)	Ob	1 mi. S. of Clear Spring, Md.
D 15	100 large calcite (poles of cleavage)	Oc	4 mi. N.W. of Hagerstown, Md.
D 16	200 large quartz (axes)	St	1 mi. N. W. of Clear Spring, Md.
D 17	200 large and medium quartz (axes)	St	Dickey Mtn., 7 Mi. N.E. of Hancock, Md.
D 18	200 large quartz (axes)	St	Cacapon Mtn., 2 mi. S.W. of Berkeley Springs, W. Va.
D 19	200 medium quartz (axes)	Sk	Fairview Mtn., 2 mi. S.W. of Clear Spring, Md.
D 20	200 medium quartz (axes)	Sk	Keefer Mtn. 6 mi. N. E. of Hancock, Md.
D 21	300 large and medium quartz (axes)	Sk	2 mi. N.W. of Hancock, Md.
D 22	200 small quartz (axes)	Swc	Main Anticline (Pl. 4), Roundtop, Md.
D 23a	100 medium and large calcite (axes)	Do (ls. memb.)	S.E. of Keefer Mtn. 6½ mi. N.E. of Hancock, Md.
D 23b	100 small and medium quartz (axes)	Do (ls. memb.)	S.E. of Keefer Mtn. 6¼ mi, N.E. of Hancock, Md.
D 24	200 small quartz (axes)	Dr. (ss. memb.)	W. Md. R.R. three-fourths mi. E. of Oldtown, Nd.

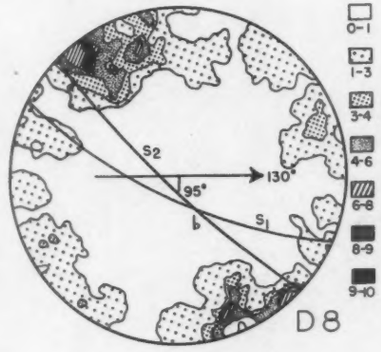
Cw---Weverton qtzite.
Ca---Antietam qtzite.
Cwb-Waynesboro fm.
Cc----Conococheague ls.
Oc----Chambersburg ls.
Sk----Keefer ss.
Do----Oriskany ss.

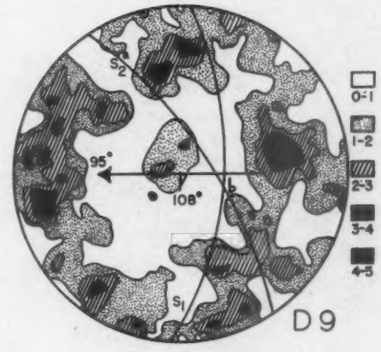
Ch---Harpers phyllite
Ct---Tomstown dol.
Ce---Elbrook ls.
Ob---Beekmantown ls.
St---Tuscarora ss.
Swc-Willis Creek sh.
Dr---Romney sh.

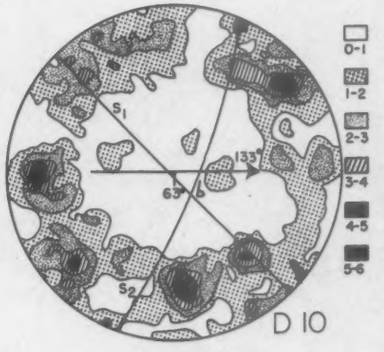


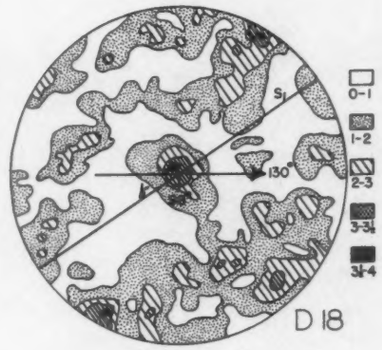


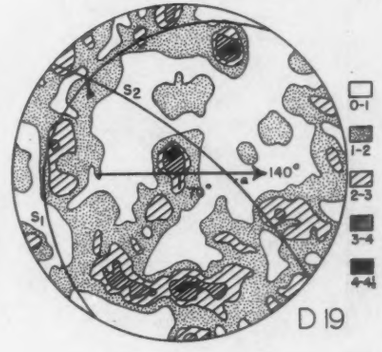


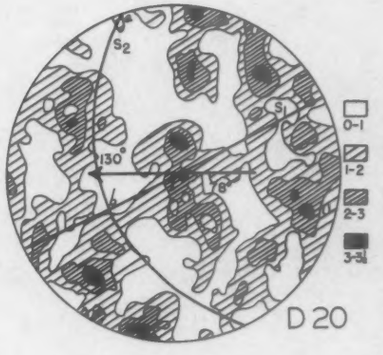


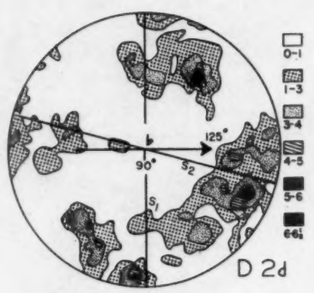


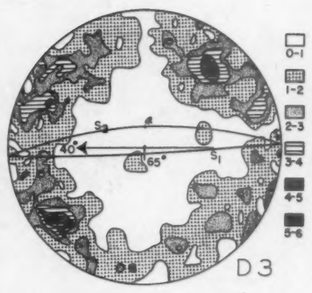


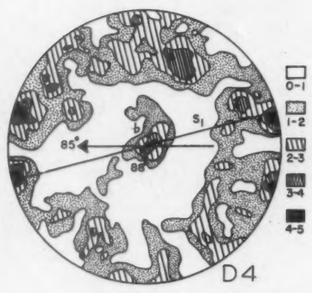


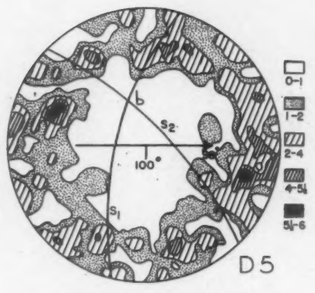


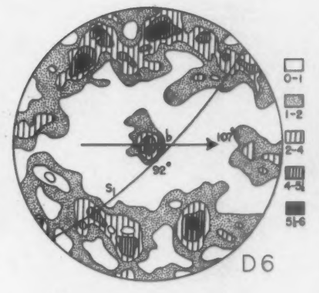


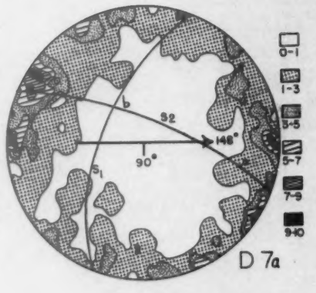


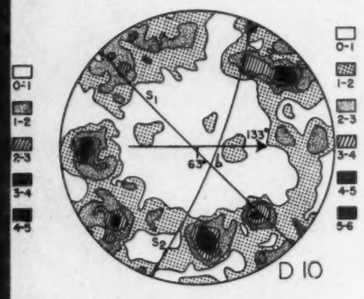


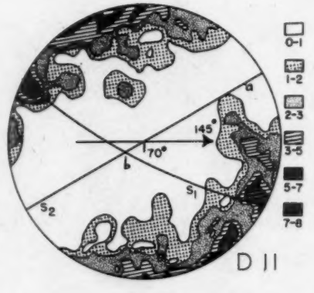


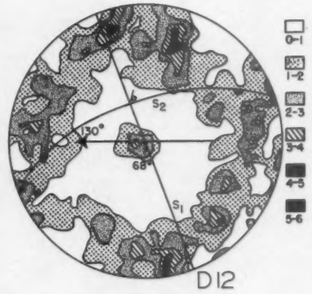


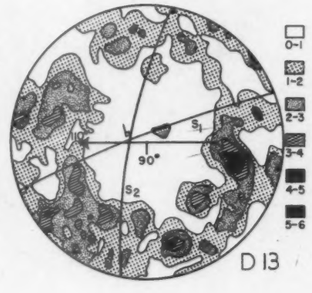


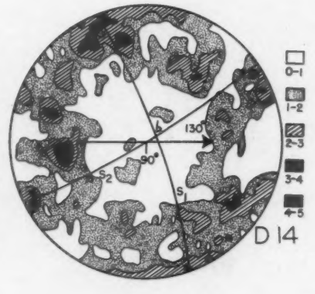


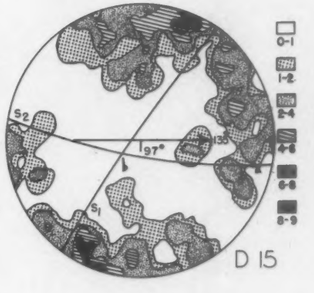


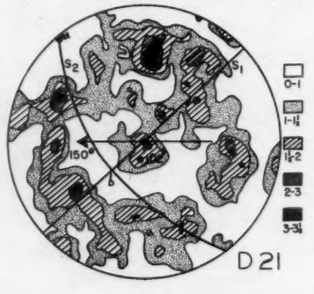


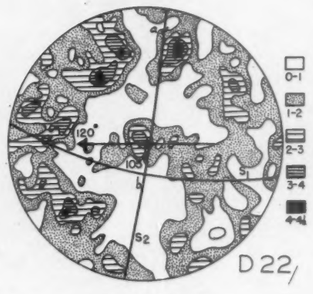


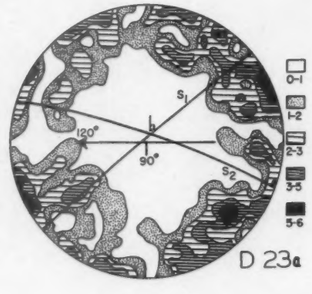


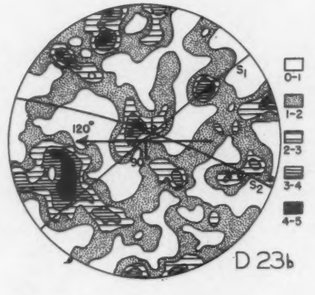


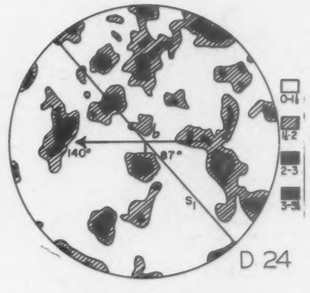












PETROFABRIC DIAGRAMS

rora and Keefer sandstones, concentrations of *c* axes are scattered. With poorer orientation of axes to the west, *ac* girdles broaden and a girdle, and the localization of maxima in a position nearly perpendicular to the flow cleavage (D 1) suggest a change from grain

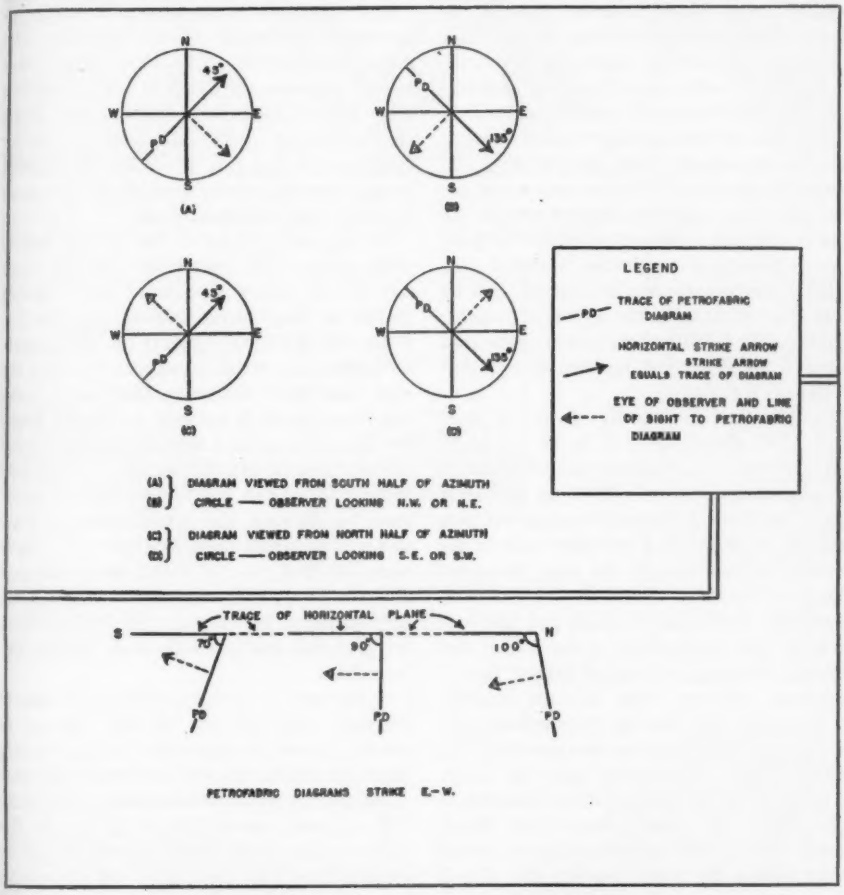


FIGURE 5. ORIENTATION OF PETROFABRIC DIAGRAMS
Upper part. Strikes of vertical petrofabric diagrams
Lower part. Dips of vertical and steeply inclined petrofabric diagrams—cross section

greater percentage of the area of diagrams is contoured. In D 16– D 21, and D 23b, the patterns contain maxima and sub-maxima that are grouped essentially at random. The regional changes in pattern suggest a greater tendency for grains farther east to rotate about axes approaching parallelism with crystallographic edges that are perpendicular to optic axes. In the Weverton quartzite, the elongation of grains, the reduction in the rotation to translation gliding at South Mountain, on the very border of the area studied.

The height of quartz maxima in the Weverton quartzite at Harpers Ferry is 6 per cent. Scattered quartz in a thin, highly deformed, calcareous layer in the Harpers phyllite, half a mile west of the Weverton exposure, develop 8-per cent maxima (D 2c), whereas in the argillaceous portion of the same specimen, quartz, maxima reach only 6½ per cent (D

2d). The lower maxima in D 2d than in D 2c are attributed to the greater cushioning effect of clay as compared with calcite. The lower maxima in the older Weverton than in the younger Harpers phyllite suggest that rock competency, as well as cushioning effect, influences the development of preferred orientations. The resistance of a competent rock to deformation will tend to retard quartz orientation. In two adjacent rocks, such as these, the greater competency of the one may retard the development of higher maxima more than the greater cushioning effect of the other. For these reasons, changes in deformation westward from South Mountain, as seen in textures, find no close correspondence in the heights of maxima. However, the heights of maxima are somewhat lower in the sandstones represented by D16–21 than in D 1, 4, and 6.

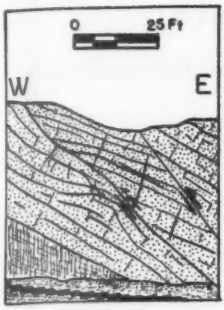
Calcite diagrams.—Calcite grains in limestones immediately west of South Mountain are extensively recrystallized and elongated in the plane of rock cleavage (Pl. 2, fig. 4). Cleavage is prominent in the calcite grains, but twin lamellae are scarce and developed only at the extreme eastern edge of the area. Elongated clusters of primary grains are recrystallized. Elongated, recrystallized grains are rare west of about the eastern third of the Valley, but equant, recrystallized grains extend farther westward, although they decrease steadily. In the east, rock cleavage is expressed principally by elongated grains, whereas toward the west, cleavage is expressed only by closely spaced rifts. In the Beekmantown limestone, 1 mile east of the western edge of the Valley, small, equant, recrystallized carbonate grains occur astride the many cleavage rifts (Pl. 2, fig. 6). It is not clear how this took place.

Optic axes and poles of cleavage in calcite have distinct preferred orientations in the Appalachian Valley and for 10 miles to the west. The typical pattern is the peripheral or *ac* girdle. The patterns for poles of mineral cleavage tend toward partial girdles with maxima located close to 90° from rock cleavage (D 2b, D 11, D 15). In optic axes diagrams, girdles generally occupy a larger arc and a larger area of the diagram inward from the periphery, and thus are less distinct than girdles in cleavage diagrams (D 5, D 7b, D 13, D 14). Maxima of poles of cleavages are 1–3 per cent higher than optic axes maxima from the same specimen (*cf.* D 7a, D 7b), or from the same general area (*cf.* D 11, D 13). Optic axes maxima seem to be located at random in the girdles. They bear no consistent relationship to rock cleavage. The approximate conformability of calcite cleavage to rock cleavage (D 2b, D 11, D 15), on the other hand, indicates translation gliding along calcite cleavage ($10\bar{1}1$). Analyses by Sander (1930) and Felkel (1929) indicate that ($10\bar{1}2$) is the important translation plane in calcite in more highly deformed rocks.

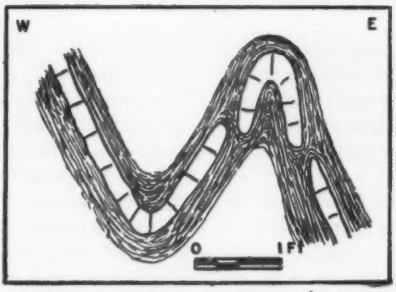
No regional changes in the general calcite girdle pattern are discernible even 10 miles west of the Valley at a point where quartz girdles no longer have distinct patterns (*cf.* D 23a with D 23b, D 17, and D 20). The heights of maxima are rather consistent for 25 miles west from South Mountain. Maxima in cleavage diagrams are 7½ per cent at Harpers Ferry (D 2b), and 8 per cent near the western border of the Valley (D 11). The maxima in D 7a and D 8 are 10 per cent, but inasmuch as the specimens of Elbrook and Conococheague limestones from which these diagrams were made were collected west of South Mountain and Harpers Ferry, evidently there is no regional significance to the maxima. The high maxima are probably due to locally more intense deformation.

A comparison of regional changes in quartz diagrams with the lack of such changes in calcite diagrams suggests that the more easily deformed calcite was still in its tectonite zone as adjacent quartz extended from its tectonite belt westward into its non-tectonite belt. The western edge of the tectonite belt defined by Fellows (1943) for quartzites and sandstones would probably have to be moved westward for some 15–20 miles to apply to the less competent limestones.

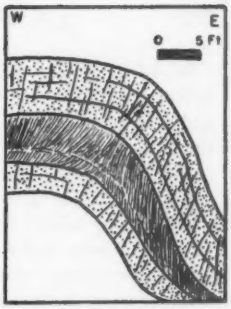
Conclusions.—The degree of quartz orientation in sandstones seems to correspond to the intensity of cleavage. As cleavage rifts become more widely spaced, orientation patterns become less distinct. Where rifts are absent, girdles do not develop and maxima are located at random and reach only 3 to 4 per cent. The correlation of strong cleavage with distinct orientation patterns, and the converse of this, suggests that grains became oriented by movements along rock cleavage surfaces.



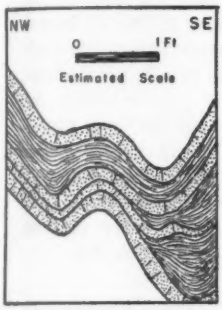
A. Thrusting, Oriskany sandstone, W. Md. R. R., c. ½ mi. E. of Spring Gap, Md.



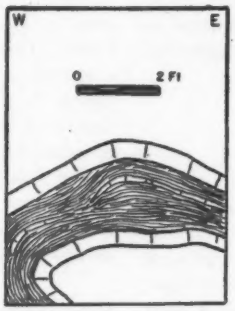
B. Thrusts beginning on limbs of anticline, Helderberg limestone, ½ mi. N. W. of Narrows Park, Md. Hwy. 36, N.W. of Cumberland, Md.



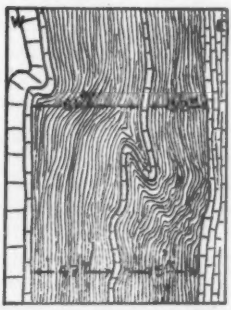
C. Distortions of shale in anticline, Jennings formation, Penna. Turnpike, 5 mi. W. of Breezewood



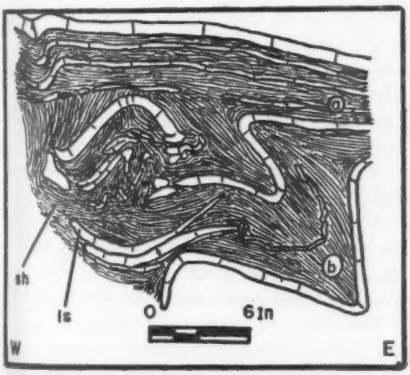
D. Changes in thickness by bedding-plane slip, Jennings formation, 2½ mi. N.W. of Amity Hall, Pa.



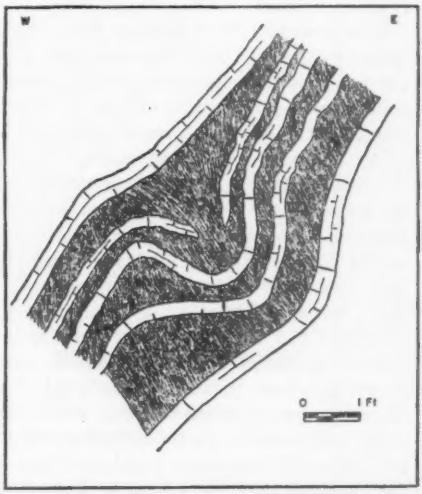
E. Distortion of shale by bedding-plane slip, Clinton formation, B. & O. R.R., Pinto, Md.



F. Adjustment of shale by bedding-plane slip, McKenzie formation, B. & O. RR., Pinto, Md.



G. Complex folding and thrusting, Wills Creek shale, W. Md. R.R., opposite Great Cacapon, W. Va.



H. Flowage of shale through break in limestone bed, Wills Creek shale, W. Md. R.R., opposite Great Cacapon, W. Va.

FIGURE 6. THRUSTS, FOLDS, AND THICKNESS VARIATIONS

In calcite diagrams, although no relationships between changes in orientation patterns and changes in cleavage have been brought out, the general alignment of mineral cleavage subparallel to rock cleavage indicates movements sub-parallel to the latter.

Distortions can be measured directly in exposed folds west of the Valley, and can be related to movements parallel to cleavage. In the Valley, where completely exposed folds are rare, distortions similar to those west of the Valley may be extrapolated once it is established that distortion proceeded by movements parallel to cleavage. Less competent shales west of the Valley probably were deformed no more readily than the more competent, but more deeply buried rocks of the Valley.

Thrusts

Small thrusts involving not more than a few beds each are common in the area and, except along initial rupture surfaces, generally conform with bedding. The best examples of small-scale thrusting are found in three exposures of upper Silurian rocks, respectively along the Western Maryland Railroad at Roundtop, Maryland, opposite Great Cacapon, West Virginia, and along the Baltimore and Ohio Railroad at Pinto, Maryland.

Relationships to Folding: Thin, alternating, competent and incompetent strata provided the most favorable environment for small-scale thrusting. Large-scale thrusts were seen only in massive sandstones and limestones (Fig. 6, A). Although regional shortening was accomplished primarily by folding, scattered local shortening on the limbs of folds took place by thrusting. Small thrusts in some places in the central Appalachians (Pl. 3) involve only the thin, competent beds, with the intervening shales having adjusted to the shortening by crumpling and folding. In other places, the intervening shales are not crumpled, even though they have been locally thickened. This suggests repeated micro-thrusting within the shales and parallel to the bedding planes. In the east limb of the prominent anticline at Roundtop, portions of the thin layer of shale have been thrust over other portions of the same layer, all between the original bounding surfaces of the bed, which have been spread apart (Fig. 4, Bed "B").

Frequent field examples show that competent beds on the limbs of folds have been repeatedly thrust directly over and parallel to themselves. Beds of gray sandstone at Roundtop ("C" in Pl. 3) have sustained repeated minor thrusting The major thrusts in the fold (Pl. 3) involve Beds "E" (red, argillaceous sandstone), "D" (green, laminated shale), and the thrust segments of "C" behaving as a unit. The anticline in B of Figure 6 has thrusts on both limbs.

The displacements involved in thrusting parallel to the limbs of folds are probably related to the bedding-plane sliding of flexure folding. Thrusts may have started where bedding had been sufficiently flexed to cause fracturing. In the troughs of tight synclines, reduction of the area between the limbs causes crowding of beds. This not only causes outward sliding parallel with bedding and crumpling of incompetent beds in the troughs, but in relatively thick, competent beds may produce thrusts out of the cores of synclines (Fig. 7).

Distortions of Stratigraphic Thicknesses

Distortions and Transverse Cleavage

Tectonic action may cause a change in the original thickness of a bed either by cleavage-forming displacements, or by repetition as a result of near-parallel thrusting.

The measurements of thickness changes and cleavage-bedding angles show that changes in the thickness of bedding in separate folds generally correspond directly to changes in cleavage-bedding angles. As the cleavage-bedding angles in any given layer become larger, the thickness of the bed usually increases. The actual percentage of increase in thickness, however, does not correspond to any given angular increase. A 50-per cent increase in thickness at the crest of a fold, for example, may correspond to an increase in cleavage-bedding angles from 0–60° in the limbs up to 90° at the crest. Where cleavage-bedding angles are about 90° both in crest and limbs, little change in thickness was noted. The relationships, therefore, can only be expressed qualitatively. The cleavage-bedding angle at the apices of all folds observed by the writer is 90°, except when bedding-plane cleav-

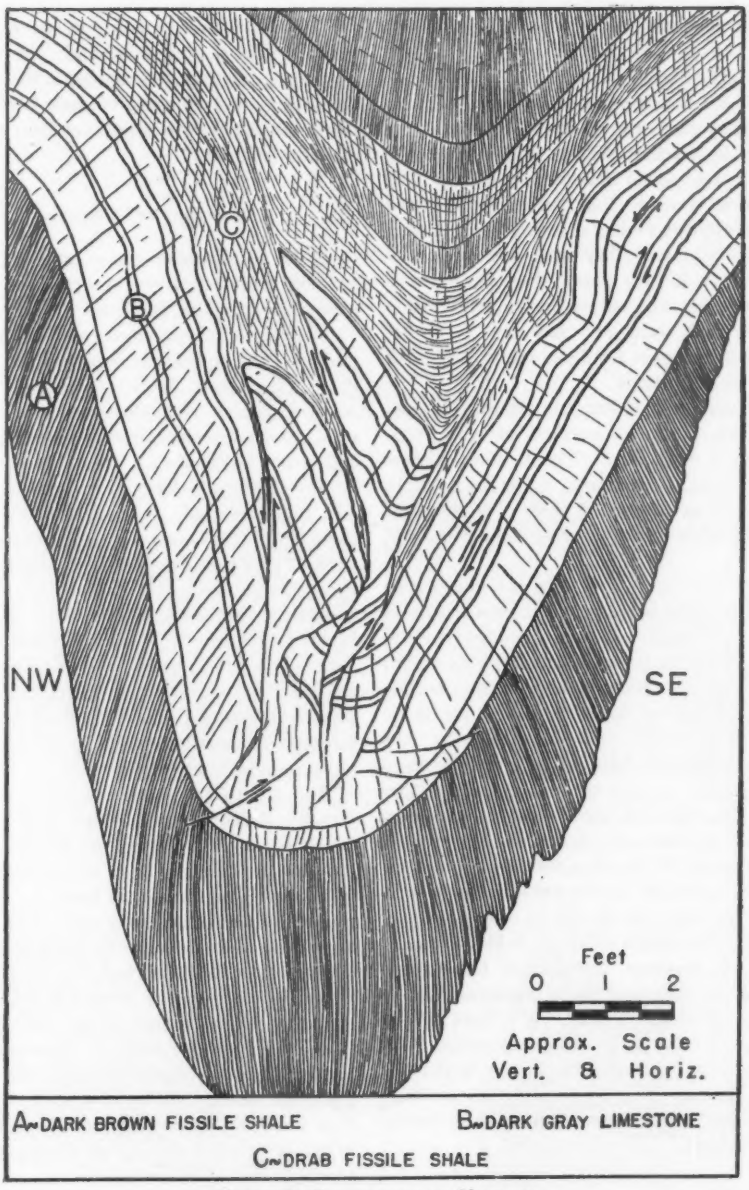


FIGURE 7. THRUSTS OUT OF SYNCLINE

age is present. In most of these folds, the thinner limb and the thinner parts of the same limb also have the smaller cleavage-bedding angles. These facts suggest that where differences in cleavage-bedding angles are observed in the same bed, but in disconnected exposures across a large

fold, corresponding differences in the thickness of the bed may be expected.

Few examples of thickness distortions associated with cleavage have been found in rocks other than shale or argillaceous limestone west of the Appalachian Valley. Shales, however, may sustain radical changes in thickness. The deduction is made that harder sedimentary rocks reacted to folding in much the same way as shale wherever they were deeply enough buried to be in their zone of flow. The textures of limestones and sandstones in the Valley suggest such behavior, but few folds are sufficiently exposed for direct measurements of thickness distortions.

In Figure 6, C–F illustrate typical thickness variations in shales interbedded with more competent rocks. In C (Fig. 6), the thickness of the shale changes from 6 feet to 6 inches within 20 feet along the limb. The cleavage-bedding angle changes accordingly from 90° to 30°.

Some relationships of folds and cleavage to thickness changes are shown in G of Figure 6. Point "a" marks a strong movement plane below which the limestone is folded, fractured, and overthrust. Slickensides were seen on the calcite stringer at "a". The reasons for differences in distortion above and below "a" are not clear. The crumpled beds of limestone have moved apart parallel to the axial plane. The shale was squeezed out to nothing in some places in the limbs, and flowed directly into the arches, as at "b". At all points, cleavage parallels the ostensible movement directions indicated by folds or thrusts in the limestone. Similar relationships are shown in H of Figure 6, in which, however, one bed of limestone is broken at the bend, thus accentuating the flowage of shale. In Bed "B", Plate 3, the thickness of the shale can be correlated with the cleavage-bedding angle. In the west limb, where cleavage is nearly parallel with bedding, the thickness is much less than at the crest or in the east limb.

Distortions and Bedding-Plane Cleavage

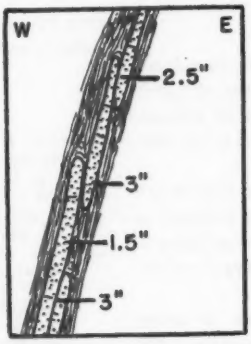
Shales are often distorted where the only evident cleavage is sub-parallel to bedding. In D of Figure 6, a layer of shale between competent beds is entirely missing in one fold and quite thick in the adjoining fold. The mechanism producing thickness changes is the gliding, interleafing, and piling-up of shale laminae or platy minerals as the competent beds sustain irregular bending.

Distortions and Thrusting

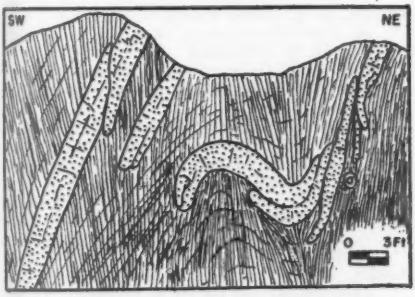
In the Appalachian region, small, parallel bedding thrusts are very common and may have a bearing on thickness measurements. The validity of measurements would depend on the size of the exposure in respect to the magnitude of the thrust. If the broken ends of the over-riding and over-ridden layers were not seen, a single limestone or sandstone bed would appear as a series of such beds. In A of Figure 8 actual small-scale thickness changes are shown in a thin sandstone. The thrusts in the sandstone ("C") (Pl. 3) result in similar repetitions. In B of Figure 8, the sandstone bed has been thrust upon itself at "a" and then folded. Thicknesses in the folded part of the bed range from 1½ to 3 feet. The southwest limb of the anticline has broken and moved upward and apart in two places. Shale occupies the large gaps. In Figure 8, C illustrates the doubling of thickness in sandstone both by overthrusting at "a" and folding at "b".

The paired distance measurements between the same surfaces of given beds in D of Figure 8 are analogous to measurements of stratigraphic thickness between key beds. In regions of folding, differences in thickness between key beds may be caused by relatively small-scale thrusting rather than by uneven deposition. The folding of the limestone bed (Fig. 8, E) again illustrates, by analogy and inference, what might happen on a larger scale. The shale between the limestone beds has weathered and been eroded more rapidly than the limestone. Traverses across the covered shale "valley" from one resistant and exposed limestone bed to the other yield distance or thickness measurements that differ from place to place owing to tectonic action rather than deposition.

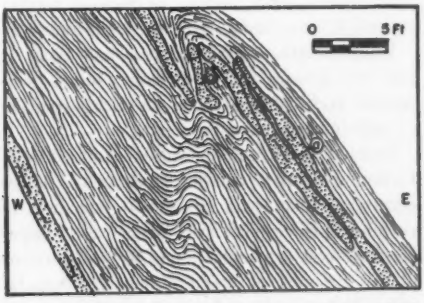
Anything like precise paleogeographic deductions in areas such as the Appalachians must be limited in the light of possible and even probable thickness distortions.



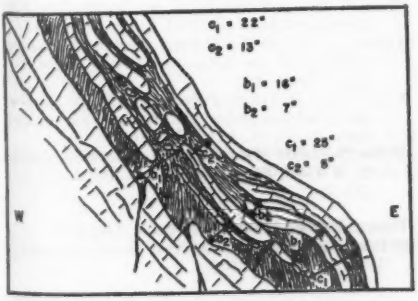
A. Variations in thickness caused by parallel thrusting, 4 mi. N.W. of Cumberland, Md.



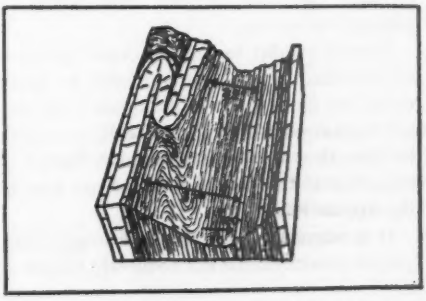
B. Thrust, folded, and distrupted sandstone bed, Jennings formation, W. Md. R.R., Keifer, Md. *c.* 1 mi. W. of Paw Paw, W. Va.



C. Thrust on limb of folded sandstone bed, Jennings formation, W. Md. R.R., *c.* 2 mi. S.W. of Paw Paw, W. Va.



D. Variations in distances between limestone beds, Wills Creek shale, 1 mi. N.W. of Hancock, Md.



E. Isoclinally folded limestone bed with minor thrusts, Wills Creek (?) shale, B. & O. R.R., Pinto, Md.

FIGURE 8. DISTORTIONS OF THICKNESS

Summary

Detailed measurements of folds, lineations, cleavages, thrusts, and preparation of fabric diagrams have facilitated analysis of deforming mechanisms and rock distortion in the central Appalachians.

Deformation decreases westward from South Mountain. This decrease may be a function of increasing distance from a center of disturbance, or of decreasing depth of burial at the time of deformation, or of both.

Calcite in younger formations is better oriented than quartz in older formations. The relative incompetency of limestone, and the ease of calcite deformation, apparently make it more sensitive to orienting processes than sandstone, even though the latter may have been more deeply buried, or located farther toward the southeast, than the limestone.

These relationships indicate that there is not one general tectonite front, but a subparallel series of fronts, one for each formation of differing relative competency.

Deforming movements caused significant distortion of primary bedding thicknesses. Where transverse cleavage is prominent, increases in thickness correspond to larger and larger cleavage-bedding angles up to 90°. Distortions of this type are observed west of the Appalachian Valley and are inferred for the rocks in the Valley.

The bedding-plane slip of competent, folded beds induced parallel slip in adjacent shales, which have often been thickened or thinned radically by squeezing-out, interleafing, or piling-up of laminae.

Thrusts parallel to bedding cause repetition of individual layers. This is difficult to detect unless the broken ends of the thrust beds happen to be exposed. Bedding-plane slip and parallel thrusting are the predominant modes of distortion in the belt of folded ridges west of the Appalachian Valley.

It is suggested that in folded areas, stratigraphic measurements are frequently subject to error because of thickness distortions caused by tectonic action.

References Cited

Becker, G. F. (1893) *Finite homogeneous strain, flow, and rupture in rocks*, Geol. Soc. Am., Bull., vol. 4, p. 13–90.

Clark, W. B. (1900) *Map of Allegany County showing the geological formations and agricultural soils*, Md. Geol. Survey, 1:62,500.

Cloos, E. (1941) *Geological map of Washington County, Maryland*, Md. Geol. Survey, 1:62,500.

—— (1947) *Oölite deformation in the South Mountain fold, Maryland*, Geol. Soc. Am., Bull., vol. 58, p. 843–918.

——, and Hietanen, A. (1941) *Geology of the "Martic Overthrust" and Glenarm series in Pennsylvania and Maryland*, Geol. Soc. Am., Spec. Paper 35.

Fairbairn, H. W. (1942) *Structural petrology of deformed rocks*, Addison-Wesley, Cambridge, Mass.

Felkel, E. (1929) *Gefügestudien an Kalktektoniten*, Jb. geol. Bundesanst., Wien, vol. 79, p. 33–86.

Fellows, R. E. (1943) *Recrystallization and flowage in Applachian quartzite*, Geol. Soc. Am., Bull., vol. 54, p. 1399–1432.

Heim, A. (1878) *Untersuchungen über den Mechanismus der Gebirgsbildung*, 2 vols., 1 atlas, B. Schwabe, Basel.

Hietanen, A. (1938) *On the petrology of Finnish quartzites*, Comm. geol. Finlande, Bull. no. 122.

Knopf, E. B., and Ingerson, E. (1938) *Structural petrology*, Geol. Soc. Am., Mem. 6.

Rogers, W. B., and Rogers, H. D. (1843) *On the physical structure of the Appalachian chain. . . .*, Trans., Assoc. Am. Geol. and Nat., 1840–42, Boston, p. 474–531.

Sander, B. (1911) *Über Zusammenhänge zwischen Teilbewegung und Gefüge in Gesteinen*, Tschermak Min. Petr. Mitt., vol. 30, p. 281–314.

—— (1930) *Gefügekunde der Gesteine*, Springer, Wien.

Schmidt, W. (1927) *Zur Quarzgefügeregel*, Fort. Mineral., vol. 11.

—— (1932) *Tektonik und Verformungslehre*, Borntraeger, Berlin.

Stose, G. W., and Swartz, C. K. (1912) *Paw Paw-Hancock folio*, U. S. Geol. Survey, Folio 179.

Turner, F. J. (1948) *Mineralogical and structural evolution of the metamorphic rocks*, Geol. Soc. Am., Mem. 30.

Van Hise, C. R. (1896) *Principles of North American pre-Cambrian geology*, U. S. Geol. Survey, 16th Ann. Rept., pt. 1, p. 571–910.

Willis, B. (1893) *Mechanics of Appalachian structure* U. S. Geol. Survey, 13th Ann. Rept., pt. 2, p. 211–282.

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